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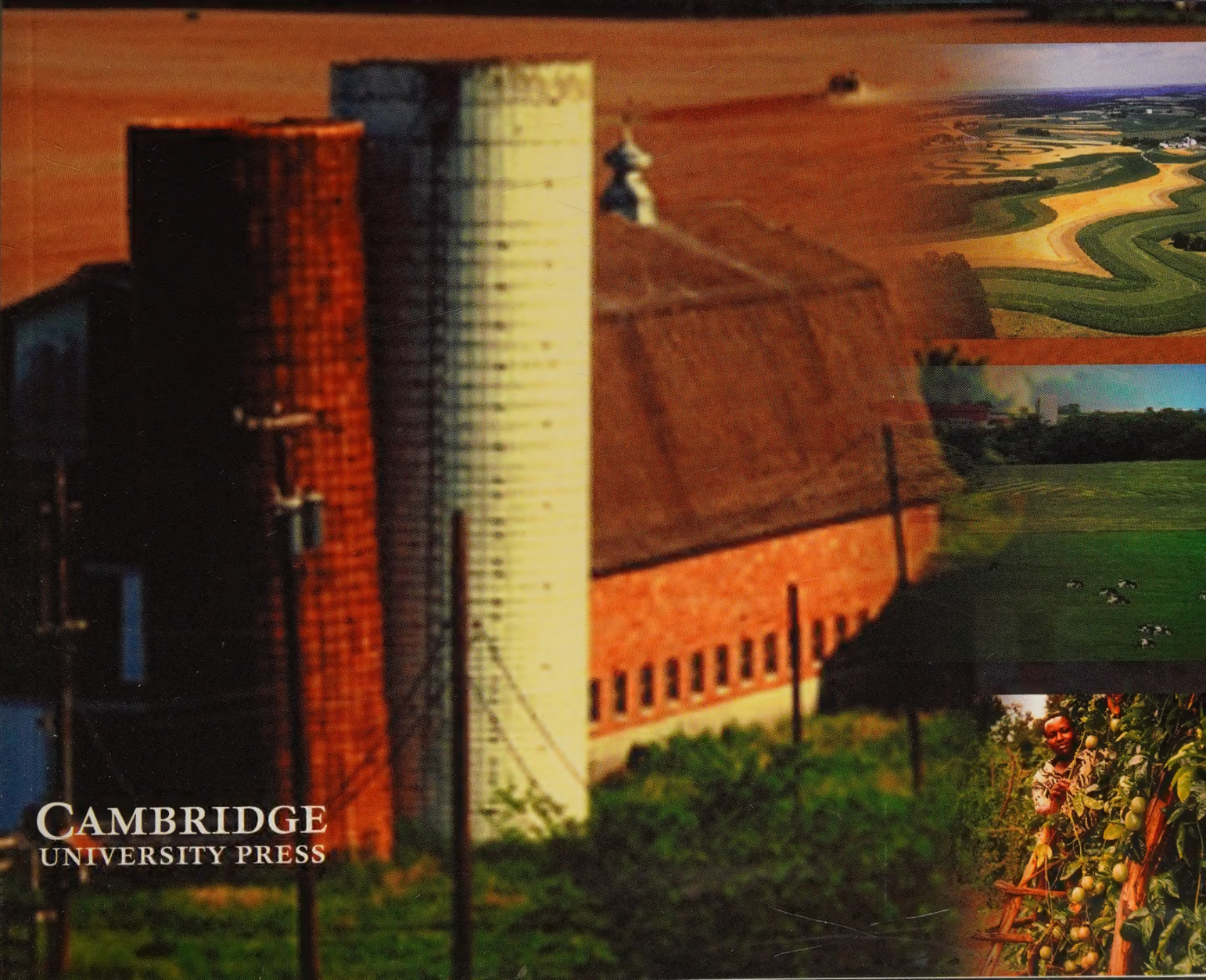

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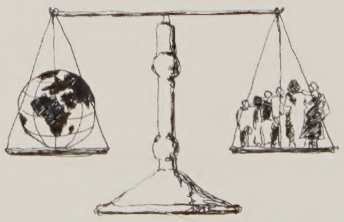

"Sustaining Earth and its People"

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Building on resources in the information age

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'We are drowning in data, swept away by information, deluged by publications, and nearly overcome by the challenge of sorting things out in search for a few drops of wisdom', we read recently. Yet, wisdom, evolving from selective consumption, critical assessment and synthesis of important ideas is sorely needed to evaluate and address our increasingly complex problems. How can any individual hope to navigate a path through the sheer mass of competing snips and bits of information that each day surpasses the total amount accessible merely 15 generations ago?

Part of the solution must be to practice careful selection, including relying on trusted people and sources to help in the selection process. This is a strategy we practice every day, of course, when we skim a local or national newspaper, consult on-line blogs and news services, scan weekly or monthly magazines and tune in to the TV news.

In agricultural science, we believe in a reiterative methodology that features replicated controlled experiments, rigorous analysis and an open peer review process to critically evaluate ideas and provide credible interpretations of data. Factual results based on experimental observations are further synthesized into recommendations. Also important are social science contributions that use quantitative analysis of survey data, as well as appropriate case studies and their application to renewable farming and food systems. Ideas from these resources are adopted, evaluated and further refined by farmers who seek to increase productivity, profitability and sustainability of their systems. As with all of us, farmers are pressed for time and must rely on useful and accurate information in order to make optimum decisions for their farms.

At times, established scientific outlets have ignored alternative approaches. This is one reason RAFS was established back in 1986 (as the *American Journal of Alternative Agriculture*). Since that time the journal has used the most precise and accepted scientific measurement techniques to broaden the discussion about the sustainability of agriculture and how best to achieve this goal.

As one key partner in this process of generating and moving relevant information, the *Renewable Agriculture and Food Systems Journal* editors have chosen to tackle a particularly complex set of issues addressing means by which farming and food systems can be improved, systems that will contribute to a secure and equitable system for the future. Meeting these goals through interdisciplinary and participatory research requires a real partnership that includes readers, authors, an editorial team and a publisher. Our success depends on attracting the best possible papers that will expand our scope by focusing on emerging challenges and by offering novel solutions rather than merely reiterating things we already know about the past and present. We also depend on reader feedback, directly to the editor, or measured by subscription numbers and evaluation criteria. Over several years, all these indicators have been positive.

Another dimension of this partnership is the *RAFS Journal* section for reviews of books, journals, web sites and other information resources that can be useful to the readership. Critical review and synthesis of materials that you find especially valuable or thought provoking are important ways that you can contribute to this learning community. In preparing reviews, it is useful to look at prior issues of our journal and others to decide what type of critique is most useful to you as a reader. We find it valuable to have a brief review of a resource, followed by a critique of the content and the interpretations, and then a recommendation of where and how you think this resource will be most valuable to others.

Reviews will be scrutinized by the editorial staff, providing credibility to the evaluation of a resource. In addition, many other journals welcome reviews of books

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and other resources. We urge our readers to submit reviews to the journals you most respect, and in this way to share opinions and new information with our broader community interested in creating an efficient, profitable, environmentally sound and equitable future food system. This is one way that you can help shape the direction of the journal and contribute to a more sustainable future.

We appreciate the contributions of Mr John Beeby and Dr Rick Welsh to this Commentary on information resources.

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Flooding to manage dodder (*Cuscuta gronovii*) and broad-leaved weed species in cranberry: An innovative use of a traditional strategy

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Abstract

The implementation of new uses for traditional cultural and pest management practices has been prompted by renewed interest in sustainable approaches for farming. The use of floods (for various durations) has been an inexpensive and historical cultural practice in cranberry (*Vaccinium macrocarpon* Ait.) horticulture. The onset of a serious economic crisis in the cranberry industry in 1999–2000 brought about an urgent need to find inexpensive methods of pest control that would allow growers to remain fiscally solvent. Initially, anecdotal evidence from several farms indicated that holding short-term spring floods suppressed dodder infestations. Based on these findings, a 2-year demonstration-style project was initiated in 2002 to determine the efficacy of short-term floods (24–48 h) for the management of dodder in cranberry in Massachusetts. The project was expanded to include evaluating a 10-day summer flood for control of broad-leaved weed species at one commercial cranberry farm. Species richness and diversity and percentage weed coverage were lower after the implementation of the 10-day flood period compared to pre-flood assessments. Weed species dead or not detected after the 10-day flood included ground nut, asters, narrow-leaved goldenrod, chokeberry and poison ivy. Comparison of paired sites (flooded and nonflooded bogs) indicated dodder stem dry weights were lower on flooded areas in three out of the seven locations in year 1. At two additional locations, the flooded bog had higher stem weights when paired with a historically low-infestation bog, which may have masked any dodder reduction from the flooding practice. In year 2, no differences in the number of germinated seedlings between any treatment pairs were noted. Data from a cranberry company representing 12% of the cranberry acreage in Massachusetts indicated a 65–89% reduction in pesticide use when short-term spring floods were implemented during 2001–2003 compared to the previous 3-year period. Short-term flooding may offer a sustainable option that can be integrated into the overall management plan for several problematic cranberry weed species, especially dodder. Additional research is warranted to further define the most effective environmental conditions needed and to validate the efficacy of short flooding events for effective cranberry weed management.

Key words: nonchemical weed control, parasitic plants, perennial weeds, flooding, cultural practices, water management

Introduction

Cranberry (*Vaccinium macrocarpon* Ait.) is a perennial evergreen vine that is native to wetland habitats and requires plentiful water supplies for its cultivation. Evolution in a wetland setting has resulted in the ability of cranberry plants to withstand periodic flooding without harm. Commercial cranberry farms in Massachusetts are associated with natural ponds or constructed reservoirs that can store the water needed for seasonal flooding and irrigation needs. A system of ditches, to facilitate movement of water for flooding and improve drainage, typically bounds the bed on all sides. Water can be used and re-used within a cranberry bog because the irrigation system and water storage reservoir are interconnected. Flooding is so important in cranberry cultivation that bogs that cannot be flooded are not considered profitable[1]. Recent research showing that spring (late water) floods[2] and fall floods[3] reduce weed and insect populations in cranberry farms has supported a resurgence of flooding for pest management.

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Dodders are obligate parasitic plants consisting of yellow twining stems that produce small clusters of white flowers[4]. The stems will wrap around the host and insert specialized structures (haustoria) into the vascular system of the host and become a strong sink for photosynthates. Swamp dodder is a serious threat to the production of cranberries in southeastern Massachusetts[5,6]. In commercial production areas, dodder spreads rapidly, damages cranberry vines significantly, develops a substantial seed bank and can reduce yields by 80–100%[5–7]. Current management strategies include the use of pre-emergence and post-emergence herbicides, hand removal of seedlings and raking dodder stems[8]. The goal is to reduce the seed bank and, to that end, controls are targeted to minimize the number of emerging seedlings, as well as the number of successful attachments made by the parasite.

Flooding has been used for cranberry pest management for many decades[9,10]. In most situations, flooding a cranberry farm is inexpensive and easy to accomplish, and many growers have incorporated flooding regimes into their regular IPM program[11]. Current flooding strategies include 30-day floods held in late spring (late water floods) for general pest control[12], 10–14-day fall floods for insect control[13,14], multi-week floods for weed and insect management[3] and 2-month floods during the summer months are recommended for perennial weed control[15]; the latter technique eliminates the crop for that year. Reports from the 19th century indicated flooding for 24–48 h in mid-May could manage black-headed fireworm (*Rhopobota naevana*)[16]. Although recent research indicated that oxygen levels, water temperature, egg hatch and plant development are important parameters for black-headed fireworm and cranberry girdler (*Chrysoteuchia topiaria*) control with short (< 72 h) floods[13,17], short floods have never been utilized for weed management in cranberry.

The reintroduction of traditional horticultural or pest management practices into modern usage encompasses multiple commodities and disciplines. Policies of fire suppression were lifted after decades of use to improve forest health in western US forest systems and improved biodiversity[18]; both fire and thinning were reintroduced to improve general forest health in ponderosa pine (*Pinus ponderosa*) in Arizona[19]. Switching from burning to mowing in lowbush blueberry (*Vaccinium angustifolia*) caused an increase in mummy berry (*Monilinia vaccinii-corymbosi*)[20]; an outbreak of *Valdensinia* leaf spot (*Valdensinia heterodoxa*)[21] in 2009 has caused growers to reintroduce burning back into their disease management regimes (P. Hildebrand, pers. comm.). Grazing was reintroduced to aid in the restoration of semi-natural grasslands with positive effects on species richness and improved habitat quality[22]. An example associated with the use of flooding includes the reintroduction of vlei (seasonally water-logged depressions) cultivation, which was determined to be a feasible option for the production of maize and rice in Zimbabwe[23]. Less traditional situations include the reintroduction of shade trees to enhance biophysical conditions in cocoa (*Theobroma cacao*)[24] and the restoration of whole agroecosytems to protect declining weed communities associated with the reintroduction of rice paddies[25]; the latter project was largely motivated by labor shortages and cost issues, a situation similar to that seen in the present cranberry example.

The inception of this project was born of necessity. At the onset of the cranberry economic crisis in 1999–2000, innovative and inexpensive control strategies were needed to control dodder and broad-leaved weeds. One large-scale cranberry operation in Massachusetts opted to hold several 18- to 30-h floods during May for dodder management. Using the lack of dodder growth as an indicator, the growers felt they had good success with these floods. Cranberry growers were also interested in using short (10-day) summer floods for broad-leaved weed control instead of stick-wiping with glyphosate, a very labor-intensive technique. It was thought that shorter summer floods would cause less yield reduction than the traditional 2-month flood. Although flooding has been a technique utilized for pest management in cranberry for decades, the use of short floods for dodder control had not been previously evaluated. In addition, holding a short summer flood for general weed control was novel for its potential to minimize significant crop loss while still obtaining weed control. If this cultural strategy is used in lieu of herbicide application, flooding would decrease production costs and provide environmental benefits due to overall lowered pesticide inputs.

The objectives of the current research were to: (1) document the anecdotal observations of dodder management with short-term spring floods using systematic data collection; and (2) evaluate the potential of integrating short floods as a sustainable practice for the management of dodder and broad-leaved weed species.

Materials and Methods

Dodder floods

Seven and five paired sites were selected in 2002 and 2003, respectively. A paired site was defined as proximal production areas at which one bog was flooded, while its neighbor was not flooded. Efforts were made to select sites that were adjacent areas of similar variety, soil type and size. Pairs were selected based on the ability of the grower to control the flooding process, knowledge of previous dodder infestations and willingness of the grower to use the flooding practice while withholding conventional weed control measures. Although this does not conform to traditional experimental design, this method has been used previously in similar demonstration-style studies[3]. All paired sites were on established (>3-year-old) cranberry farms located in Wareham, Massachusetts and Carver, Massachusetts. Three varieties (Early Black, Howes and Stevens) were used in the study.

Table 1. Weight of dodder stems collected from seven Massachusetts cranberry bogs that were flooded (F) or not flooded (NF) in 2002. Stems were collected 10 weeks post-flood.

Location–treatment	Dates	Flood (h)	Stem dry wt (g/m^2)[1]	Historical infestation
1-F	3–5 May	36	0.90	High
1-NF			1.42*	Moderate
2-F	13–15 May	48	1.51	Moderate
2-NF			2.10	Moderate
3-F	14–16 May	36	0.92*	High
3-NF			0.42	Low
4-F	3–5 May	36	0.16	Low
4-NF			0.97*	Low
5-F	10–11 May	36	0.69	Moderate
5-NF			0.37	Low
6-F	10–11 May	36	0.41	High
6-NF			0.71*	Low
7-F	6–7 May	24	0.54*	Moderate
7-NF			0.30	Low

[1] Asterisk indicates significant difference between treatment pairs according to Student's *t*-test ($P = 0.05$).

Floods, which were 30–36 cm deep and covered the vine tips, were held for 24–48 h between May 3 and May 16 in 2002 and for 45–50 h starting May 12 in 2003. Our plan was to place pouches containing known numbers of dodder seeds onto each of the paired sites approximately 2 weeks prior to the flood, collect the pouches and evaluate germination. However, in 2002, all bogs were flooded prior to pouch placement due to severe infestations of black-headed fireworm (*R. naevana* Hubner). Black-headed fireworm larvae can be devastating and the grower needed to take control actions quickly. Short-term floods are known to control larval populations in lieu of insecticides[13,26,27]. Given the circumstances, we made alternate plans to evaluate the dodder populations in 2002.

In 2002, approximately 10 and 20 weeks post-flooding, dodder stems and seeds were collected, respectively. The entire bog was inspected for the presence of dodder and selected areas of representative growth. Six 465-cm^2 quadrats were randomly placed in the infested areas. Paired sites were harvested on the same day. Dodder stems or seeds were removed by hand from the uprights (vertical stems) in the field when possible. If not, the upright was cut, and the dodder plant and cranberry upright were separated in the laboratory. Field samples were placed in plastic resealable bags and a cooler was used for transport back to the laboratory. Stem samples were transferred into paper bags, dried at 60°C for at least 48 h and dry weights obtained. Seed capsules were crushed and seeds separated from the chaff and counted. No germination tests were conducted in 2002.

In 2003, six pouches containing 200 scarified dodder seeds each were secured to the bog floor with a tent pin at each paired site by April 15. Seeds were physically scarified by grinding the seeds with sand (1 : 1 mix) for 2 min in a mortar and pestle. The pouches were constructed to permit movement of the flood water with the seeds while prohibiting unnecessary release of seeds onto the commercial farm. The seeds were placed in a piece of muslin cloth (11.4 × 11.4 cm, folded in half), which was then placed in the center of a pouch made of 18 × 16 mesh insect screen (10.2 cm × 20.3 cm, folded in half). The pouch was sealed on three sides with silicone caulk and allowed to dry. The open end was folded over and secured with staples, which could be removed later.

After the removal of the flood waters, all pouches were retrieved from the paired sites. The pouches were opened in the laboratory and seeds removed. Seeds were placed in glass Petri dishes lined with moistened filter paper and incubated at 22°C. On a regular basis, emerged seedlings were counted and removed from the dishes. Percentage germination was determined after 4 weeks.

Summer flood

A 10-day flood was maintained on a 0.9 ha Howes bog in South Carver, Massachusetts from July 2 to July 11, 2002 and it was paired with a 0.25 ha Howes bog that was not flooded. Ten 1-m^2 quadrats were marked with pin flags on the flooded and nonflooded bog. Prior to the flood (June 20, 2002) and after the removal of the flood (July 24, 2002), plant community parameters were assessed. Identified plant species were assigned to one of 10 possible cover classes: 0% = 0, <1% = 1, 1–5% = 2, 6–10% = 3, 11–25% = 4, 26–40% = 5, 41–60% = 6, 61–75% = 7, 76–90% = 8 and 91–100 = 9. Mean species value (MSV), species richness (number of species), evenness and Shannon's diversity index were calculated. MSV, an indication of average plant coverage, was calculated by dividing the sum of the cover class values for the sampling unit by the number of species or the number of plots, as appropriate.

Statistical analysis

Data were analyzed with Statistical Analysis System software[28]. Comparisons of measured parameters between

flooded and nonflooded treatment areas were made by Student's *t*-test ($P = 0.05$).

Results and Discussion

Dodder management

Dodder stem dry weight was lower on the flooded area compared to the nonflooded area at three sites, higher at two sites and was not affected at two sites in 2002 (Table 1). To explain these variable results, we considered the possibility that the nonflooded bog of each pair was selected by the grower because it was known to have low dodder pressure and thus would be a low-risk bog to include in the study. Consequently, historical information was obtained on the dodder populations for each bog (Table 1). At sites 1, 4 and 6, the flooded areas had lower dodder stem weights even though the historical infestation of dodder on the nonflooded bog was either equivalent to or less than the flooded bog. At site 2 (both areas had equivalent histories of infestation), the flooded area trended toward lower stem weights, but was not statistically significant from the nonflooded site. At sites 3 and 7, the flooded area had higher stem weights (and historically higher dodder infestations) than the nonflooded area. We wondered if the higher dodder stem weights were due to the failure of the flood and/or very high dodder pressure? Would the dodder stem production have been even higher on the flooded areas if they had not been flooded at all? The use of the pouches may have helped in the assessment of the relative success of the 2002 study.

Seeds were collected from four out of the seven potential sites; three sites were harvested for fruit prior to seed collection. Flooding did not affect the number of seeds produced (data not shown). Seed number may not have been the best assessment of reproductive impact, so changes were made for the 2003 tests to evaluate germination (viability) instead of the number of seeds. In the second year, we used seed pouches for evaluation of the flood instead of the labor-intensive process of biomass and seed collection. No differences were noted for any of the flooded/nonflooded pairs for dodder seed germination in 2003 (data not shown).

It is difficult to know if treatment differences with the pouch method were not detected because the floods did not work in 2003 due to timing (see below) or other issues, or if this method was inferior in measuring dodder response. Retrospectively, using a combination of approaches (e.g., biomass assessment, seed collection and seed germination) may have clarified treatment effects. We hypothesize that the timing of the flood may be critical to adversely affect the dodder population. Seedling emergence patterns for dodder have been tracked yearly since 1997 at the University of Massachusetts Cranberry Station[29]. In 2002, floods were started 16 days after first seedling emergence (April 17) and peak emergence occurred on *c.* May 20–26. In 2003, first seedling emergence was on May 5 and the floods were started 7 days later; peak emergence occurred between May 29 and June 2. It is likely that seedlings are more vulnerable to flooding than seeds; allowing more time to elapse between first seedling emergence and flood initiation may be more effective (as seen in 2002). Future research should examine the impact of flood duration, flood initiation and environmental factors (e.g., water temperature and dissolved oxygen levels) to further define the best way to utilize short-duration floods for dodder control.

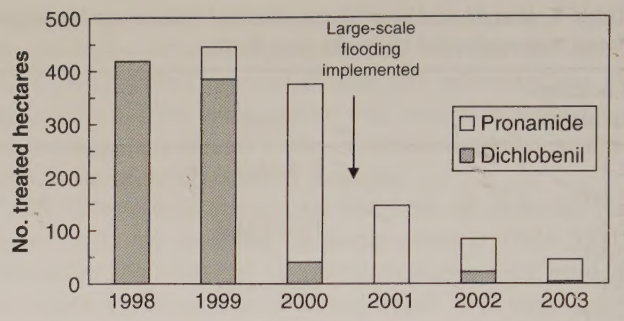

Figure 1. Herbicide applications for dodder management by a Massachusetts cranberry company before and after the large-scale adoption of short-term (24–48 h) flooding practice (A.D. Makepeace Company, pers. comm.).

The role of saturated soils on weed seedling emergence has been studied from the perspective of maintaining well-drained soils. For example, a greenhouse study showed that the emergence of hairy beggarticks (*Bidens pilosa*) seedlings decreased with increased duration of shallow (1.5 cm) flooding following planting[30]. Similarly, although flooding detrimentally impacted Virginia buttonweed (*Diodia virginiana*), the emphasis was to encourage managers to minimize water use in turfgrass situations[31]. On the other hand, manipulation of flooding regimes has been investigated for weed management potential in rice (*Oryza sativa*). A greenhouse study on two species of morning glory (*Ipomoea wrightii* and *Ipomoea lacunosa*) indicated successful emergence was related to the number of days after planting, as well as the initiation date and depth of the flood; the response also varied by species[32]. Germination of texasweed (*Capernoia palustris*) was inhibited, while the soil was constantly saturated or flooded to a depth of 10 cm for 30 days[33]. Dodder is not a weed problem in rice and no research has been pursued for dodder management in the rice system. The purposeful use of floods on a dry-cultivated crop to control dodder is a new application of a traditional strategy.

Short-term spring floods are being used periodically by the cranberry grower community[34]; this indicates that the practice must be efficacious since it is being implemented on working farms. Our grower-cooperator, whose farms represent 12% of the total Massachusetts cranberry acreage, provided 6 years of pre-emergence herbicide use data for dodder control (Fig. 1). These data indicate a reduction in pesticide use for dodder management due to the

Table 2. Effect of a 10-day summer flood (July 2–11, 2002) on several plant community parameters on a commercial cranberry bog in southeastern Massachusetts ($N = 10$).

	Unflooded		Flooded	
Measured parameter	**Pre**	**Post**	**Pre**	**Post**[2]
MSV[1]	1.11	1.17	0.91	0.67*
Species richness	6.30	6.00	4.50	2.50*
Evenness	0.90	0.90	0.87	0.78
Shannon diversity index	1.61	1.59	1.22	0.73*

[1] MSV, mean species value; coverage value divided by the number of species in the treatment. Species richness = mean number of different species present per plot. Evenness describes the distribution (equitability of abundance) of the species.
[2] Asterisk denotes significant difference between pre- and post-flood values at $P < 0.05$ according to Student's *t*-test.

implementation of short-term spring floods during 2001–2003 (L. Lemmertz and A.D. Makepeace Company, pers. comm.). Compared to the previous 3-year period (1998–2000), herbicide inputs for the control of dodder decreased by 65–89%. The company reported that, in most situations, they were pleased with the dodder management obtained from the use of the spring floods. Short-term floods hold promise for integration as a sustainable and nonchemical practice for dodder management in cranberries but more research is certainly warranted.

Broad-leaved weed management

The 10-day flood had a detrimental effect on several weed species and resulted in the reduction of overall weed coverage. Student's *t*-tests indicated that MSV, species richness and diversity were lower for the flooded bog after the flooding treatment than prior to the flood (Table 2). Measured survey parameters were the same for the nonflooded bog before and after the flood. When looking at individual species, post-flood parameters were lower for many species than pre-flood values (data not shown), but *t*-tests were not significant. Several weed species were dead or not detected after the flood. Species not detected post-flood (which were present prior to the flood) included ground nut (wild bean), asters, slender-leaved goldenrod, chokeberry and poison ivy. Some negative impacts of cranberry were noted (e.g., bog edges were severely impacted from the warm water, which necessitated flood removal at day 10). Additional work is needed to validate the efficacy of short summer floods for reducing perennial weed populations as demonstrated at the single site used in the present study.

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Communicating imperceptible product attributes through traceability: A case study in an organic food supply chain

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Abstract

Companies in the food industry are driven to improve their traceability for several reasons. The primary reasons are food safety and quality. Another is the response to the increased interest among consumers in imperceptible product attributes such as organic, fair trade, dolphin-safe and non genetically modified (non-GMO). Such attributes are hard to distinguish and thus require generally enhanced traceability in order to verify their existence. This has led to an emergent area in which actors engage in gaining and maintaining traceability and communicating it to the consumers. This paper describes the relations between the actors in a supply chain (SC) in the field of organic food systems. It examines the objectives each actor has for gaining and maintaining traceability throughout the SC. The focus on organic relates to the challenge for the companies to ensure this imperceptible product attribute throughout the entire food system. A single case study was conducted in an organic food system providing organic ice cream products. The data collection included semi-structured interviews, observations, a review of internal documents and a survey among the participating companies. The findings illustrate and elaborate on the objectives companies have for engaging in traceability. The objectives identified are divided into three categories: food safety and quality, managing the SC and internal resources and communication with consumers. The survey confirms the results from the interviews that all actors want to engage in traceability. They prioritize the objectives differently, however. The study highlights the value of close relations between the actors when addressing consumer concerns regarding product and process characteristics, such as the imperceptible organic attribute.

Key words: case study, consumer communication, food supply chain, food system, imperceptible product attributes, organic food, supply chain management, traceability

Introduction

Companies in the food industry are driven to improve their traceability for several reasons. Primary among these are food safety and legal aspects[1]. Another is the increased interest among consumers in imperceptible product attributes such as organic, fair trade, dolphin-safe and non genetically modified (non-GMO). This has led to an emergent area for actors to engage in gaining and maintaining traceability to ensure these qualities and to communicating them to consumers[1]. Such attributes are, however, hard to distinguish since they cannot be judged either on their appearance or on past experience[2]. Thus, they generally require more qualified traceability to verify their existence[3]. One concrete example is the growing trend toward organic food and the importance of origin to consumers. This trend is driven in part by consumers' increased concern for food safety, animal welfare, as well as the environmental and ecological impact of food processing and production[4]. A future challenge for companies is how to ensure and communicate to consumers that their organic products are organic in all aspects from farm to fork (i.e., the entire food system).

Both products and activities are important entities to trace[5,6]. For products to be traceable, unique identification of them or of groups of products is required. This can be achieved through labeling directly on the product or package and through record keeping. The activities have to be traceable to describe the history of a product through the different processes/activities it passes on its way through the supply chain (SC)[6]. The history of a food product can include practical, physical as well as ethical aspects[1].

Chain traceability is dependent on the participation of all the actors in the SC. Successful implementation calls

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for co-operation among them all[7,8]. As in all chains, the weakest link determines its capacity. In the SC management literature, the importance of collaboration is also highlighted as a general concern. Since today's competition is no longer between companies, but rather between SCs[9–11], managing complex food SCs has proven to be challenging. It is imperative that all actors contribute to successfully maintain traceability throughout an SC.

This challenge is shown, for instance, when companies assume that by optimizing their own interests they also maximize the SC's interests. To overcome sub-optimization in a food system or SC, it has been suggested that management focus on aligning the incentives[12]. Contracts, sharing of information and trust are different ways to govern the relations and align the incentives[12,13]. A contract is the solution that Narayanan and Raman[12] most strongly suggest. Coming from a more sociological research tradition, Brom[14] focuses on the importance of building trust in the relations between actors in an SC.

It is thus of great importance to understand these relations as well as the actors' different objectives for engaging in traceability. This paper describes the relations between the actors in an SC in an organic food system. It examines the objectives the actors have for gaining and maintaining traceability throughout the chain. The focus on organic relates to the challenge for the companies to ensure this imperceptible product attribute throughout the entire food system. The core research question is: Why do actors in food SCs want to gain and maintain chain traceability?

The paper starts with a theoretical elaboration of three categories of objectives for food system traceability derived from the research literature. This is followed by method and case descriptions. Results from the study are then analyzed. The paper concludes with practical aspects of traceability and their use in the food system, linking them to the theoretical aspects.

Objectives for Food Traceability

Actors in food SCs have different objectives for their efforts to gain and maintain traceability[1,6,15–18]. According to Golan et al.[16], 'different objectives help drive differences in the breadth, depth and precision of traceability systems'. These objectives play an important role in chain traceability, since one actor's objectives place demands or limitations on the traceability in the SC and thereby on other actors[6].

The objectives found in the literature can be grouped into categories. Inspired by Golan et al.[16], three categories of objectives were selected: food safety and quality, managing the SC and internal resources and communication with consumers.

Food safety and quality

Food safety is a consumer concern[14] and deals with whether or not food is fit for consumption[19]. Although food safety is considered an obligation to the consumer that has to be assured by governments through legislation and regulations[19], several illnesses caused by food-borne pathogens are still reported every year. The number of unrecorded cases is estimated to be large according to the Swedish National Food Administration[20]. Legislation can be regarded as 'a driving influence in this respect', according to Furness and Osman[18].

Food quality of today is a complex concept with several components[19]. It does not only encompass the traditional view of appearance (looks good), technical quality (tastes good) and biological quality (does good or at least no harm), but also includes aspects that express cultural, environmental and ethical values[21].

Traceability is considered essential for food safety and quality control since it helps companies isolate products with deficiencies and find the cause[16]. Hence, traceability can contribute to resolving food safety and food quality problems. An incentive for companies to invest in traceability is the potential reduction of the production and distribution of unsafe or poor-quality products. This minimizes the risk for bad publicity, liability and recalls. However, traceability as such does not provide safer food. It only offers information as to whether or not control points along the SC have been met[16].

Managing the supply chain and internal resources

Managing the SC marks the difference between the successful and failed firms[16]. This is because the movement, storage and control of products through the chain are very costly and of competitive importance for companies. This is particularly the case in the food industry where margins are low. The traceability system can be an important tool in such competition as a crucial way of determining the most efficient way to produce, assemble, warehouse and distribute products. The more co-ordination is valued in the SC, the greater will be the benefits from a traceability system[15,16]. The interaction and relations between companies in an SC affect the overall traceability from farm to fork, and it is argued that the performance of an SC can be improved by alignment of the actors' incentives through contracts, sharing of information and/or trust[12].

Ghosh and Fedorowicz[22] state that trust, power and contracts are important elements in enabling relationship governance between different actors in an SC. Their study shows that 'trust works in conjunction with power and contracts'. However, they point out that when the power is exercised it is likely to have a negative impact on trust. Contracts can be used to increase the level of trust between actors in cases of unequal power levels, emanating from, for instance, differences in company size[22]. Poppo and Zenger[23] and Seshadri and Mishra[24] conclude that trust and contracts are complementary and not substitutes for one another as researchers in sociology and economics in general claim[13,23].

Table 1. List of food industry and consumer concerns.

Deblonde et al.[19]	Beekman[26]	Coff et al.[1]
Food sector concerns	*Consumer concerns*	*Consumer concerns*
Food security	Pubic and personal health	Animal welfare
Food safety	Genetic modification	Human health
Food quality	Animal welfare	Methods of production
Food sovereignty	Natural environment (sustainability)	Terms of trade
Human welfare	International justice (fair trade)	Working conditions
Animal welfare	Preservation of regional foods	Quality (intrinsic qualities: taste, composition, etc.)
Ecological sustainability		Origin and place
Transparency		Trust
Traceability		Voice
		Transparency

Co-ordination in the SC is needed to ensure not only a timely flow of materials and information. It also influences traceability, which is dependent on the flow of materials and the recorded information along the flow[22].

Communication with consumers

The shift in perception of food quality among consumers from the traditional view to more qualitative aspects reflects increased concern for the environment, animal welfare and culture, according to Beer[25]. He states that these qualitative aspects carry associated costs, but also provide companies in the SC with an opportunity for differentiation and premium prices[25].

> With the food we choose, we make a statement about our identity and connect ourselves with other people who make the same kind of food choices[1].

Beekman[26] states that consumer concerns can also regard: (i) public/personal health, (ii) genetic modification, (iii) animal welfare, (iv) natural environment (sustainability), (v) international justice (fair trade) and (vi) preservation of regional foods. He calls these[26] 'moral concerns' as they all 'go beyond merely personal interests like availability, convenience, price and taste'. Beekman[26] elaborates on the distinct difference between the first two and the others. With the first two, 'it is perfectly possible to test products to ensure the accuracy of information about food safety or genetically modified ingredients', whereas the last four 'qualities can only be verified with the help of recorded identifications of product (hi)stories through the food chain'. There is also a relation between consumers' preferences for organic food and their concerns for the above-mentioned parameters, such as animal welfare or the environment[4]. Michalopoulos et al.[2] agree that consumers nowadays have concerns or preferences regarding 'imperceptible', 'intrinsic' or 'unobservable' food characteristics that cannot be judged either on their appearance or on past experience. The absence of appropriate information on imperceptible food characteristics limits the ability of concerned consumers to consider ethical issues in their food consumption and purchasing[2]. Consumer concerns thus present an opportunity for food companies or SCs to communicate added values to consumers at the point of purchase. Table 1 presents a framework of concerns derived from the food sector and from consumer concerns. The challenge for companies is to turn the traceability concerns of the actors in the SC into value-added information that attracts consumers.

Method

This paper presents an exploratory, single case study including several actors in a food system providing organic ice-cream products. It includes companies mainly, but not exclusively, situated in Sweden. The case study was chosen as a research strategy in accordance with Yin[27]. This allows for an in-depth understanding of the contemporary phenomena being examined in the selected food system. It is a preferred strategy when the study is exploratory in nature[27].

The study was conducted in the food industry since chain traceability is a current topic in that sector. This is due not only to recent food scares and tougher legislation in Europe, but also to increased consumer concerns.

This research aims to gain knowledge of traceability interactions between SC actors. A systems approach was thus applied, since the sum of the traceability performances within the companies does not necessarily equal the total traceability performance of the entire SC. The issues examined are described and elaborated from the characteristics of the whole food system, since the knowledge is dependent on the entire system.

Case description—the food system studied

The focal company was chosen because it was a special case, due to interesting characteristics. It produces entirely organic food products and is about to engage in a change process to make its entire SC more transparent. The goal of this change is to better communicate the organic product attribute and its origin to the consumers. Traceability is high on the company agenda due to customer and consumer demands, and the company's internal strategy of food safety and quality control. Information from the company

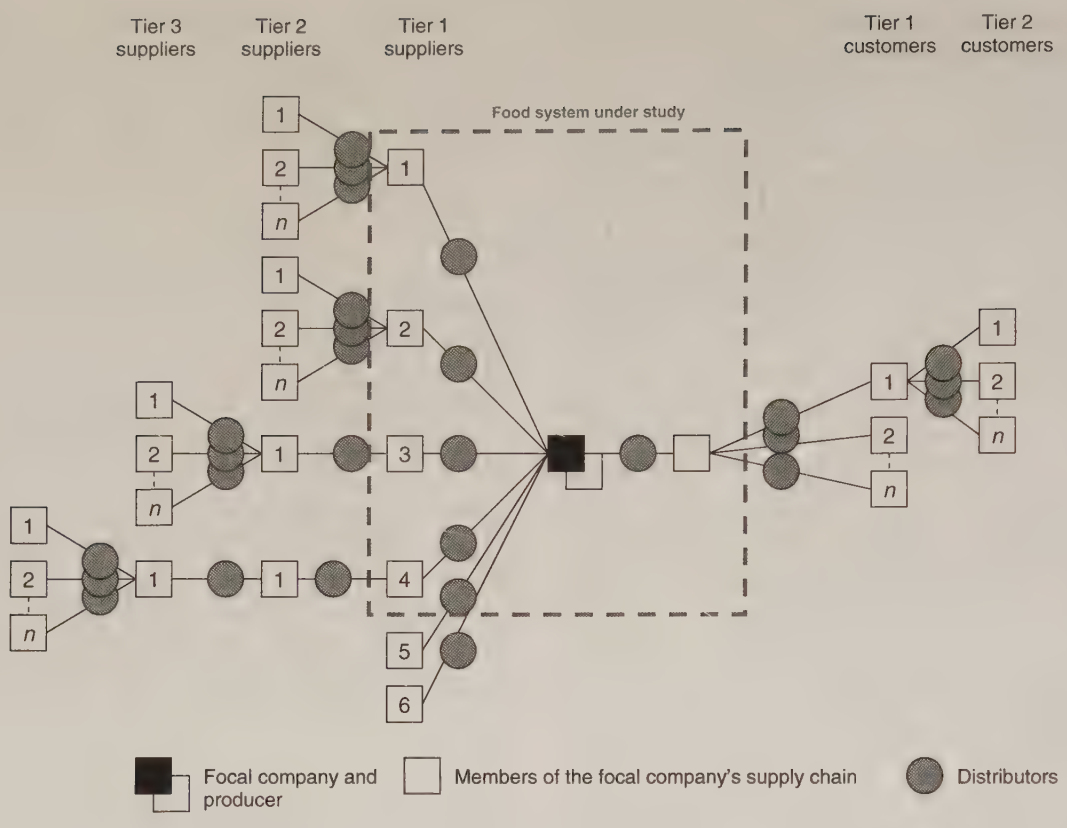

Figure 1. The different actors (the amounts of actors are illustrated by the numbers) in the SC for the product studied, inspired by Lambert and Cooper[11], and the selected focus of the study (i.e., the food system under study).

Table 2. Key characteristics of the companies involved.

Company	Main function in the SC	Founded	Employees	Turnover	Organic versus conventional
Focal company	Brand owner	1911	4	0.4 million €	Organic
Producer	Food production	1937	36[1]	3 million €	Mixed
Supplier 1	Food production	1964	600	270 million €	Mixed
Supplier 2	Food production	1982	100	50 million €	Mixed
Supplier 3	Food production	1873	1800	900 million €	Mixed
Supplier 4	Wholesaler	1976	5	2 million €	Organic/fair trade
Distributor	Distribution and warehousing	1950	700	140 million €	Mixed

[1] Yearly average.

was easily accessible due to their genuine interest in organic food and traceability.

This case study encompasses the four main suppliers of ingredients (milk/cream, sugar, eggs and flavor) of a specific ice-cream product in the focal company's product range. In addition to the four suppliers, the focal company (the brand owner), the producing company and one distributor are included (see Fig. 1).

The focal company has a long and strong tradition of being careful with ingredients; trust and personal relations are of great importance when choosing suppliers. In 1993, the company was KRAV certified (KRAV develops organic standards and inspects food and food products to meet these standards in Sweden). All of the products of the focal company are organic. In recent years, they have outsourced their production to another company, which is family-owned and also recognized for manufacturing quality products (information provided by the production company and their homepage). The vision of the focal company is to communicate product attributes, such as origin and production history to the consumer through their web page and packaging. Key characteristics of the companies involved are presented in Table 2.

Data collection

Data were collected through semi-structured interviews, a review of internal documents and observations of the

Table 3. Interview respondents and procedure.

Company	Function	Procedure	When	Observation
Focal company	CEO	Taped, semi-structured	Several occasions	–
Producing company	CEO	Notes, semi-structured	Several occasions	Yes
	Quality manager	Notes, semi-structured	Several occasions	
Supplier 1	Production manager	Taped, semi-structured	2009-03-13	Yes
	Consultant—organic food	Taped, semi-structured	2009-03-13	
Supplier 2	Market manager	Taped, semi-structured	2009-03-13	–
	Product manager	Taped, semi-structured	2009-03-13	
Supplier 3	Sales manager	Notes, semi-structured	2009-03-23	–
	Environmental and quality manager	Notes, semi-structured	2009-03-23	
Supplier 4	Purchaser	Taped, semi-structured	2009-09-17	Yes
Distributor	Warehouse manager	Taped, semi-structured	2009-10-30	Yes

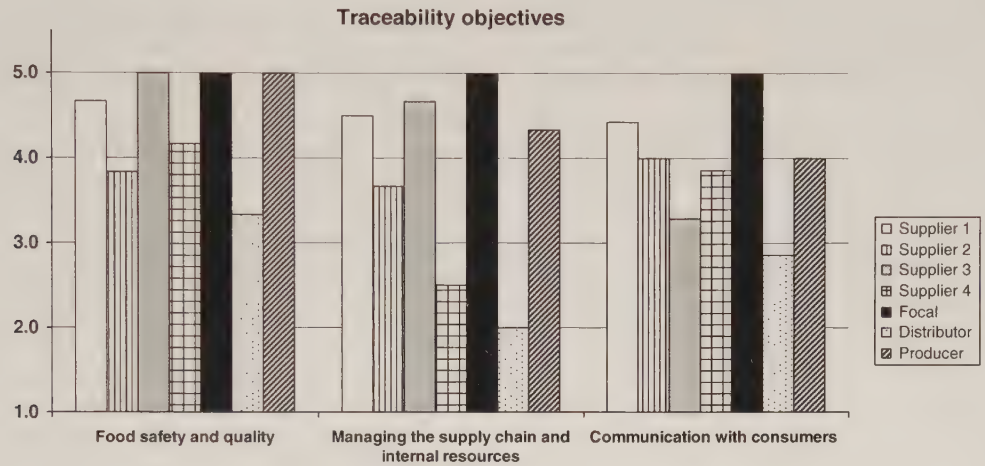

Figure 2. Aggregated survey answers in the three categories of traceability objectives indicated on a five-point scale (1–5) if they disagreed, partly disagreed, had no opinion, partly agreed or agreed.

production and the storage sites. The observations followed the flow of products through the process and were conducted to achieve a clear picture of the process. This is in line with Yin[27] who argues that the data in a case study can come from many different sources. Respondents and interview procedures are presented in Table 3. The interviews were complemented with a survey completed by the participating companies to encompass quantitative aspects of the actors' traceability objectives. The survey consisted of 19 statements regarding traceability objectives. The respondents indicated on a five-point scale if they agreed, partly agreed, had no opinion, partly disagreed or disagreed.

The collected data from the interviews were analyzed by coding the interview material into different thematic groups related to the actors' traceability objectives and the interaction between the actors. The data from the survey were analyzed through graphical comparisons as shown in Figure 2.

Observations were used to gain deeper insights and an overall understanding of the actual physical flow and the related flow of information.

Why Actors Engage in Traceability—Empirical Results

The interviews all revealed that the focal company, as well as its suppliers, considers traceability an important matter. A contributing reason mentioned by most of the respondents was a change in consumer needs to know more about products, such as imperceptible attributes. In line with this, they prioritize the objective of communicating with the consumers.

The chief executive officer (CEO) of the focal company used herself as an example of a consumer when explaining why the focal company engages in traceability. As a consumer she wants to know what she is buying, how it is transported and where it is from. If the product is labeled 'organic', she wants to be sure that it is entirely organic. Based on the CEO's personal values, the bottom line of the focal company is to 'provide more information to the interested consumer' through traceability. In addition, this ambition to use traceability leads to increased food safety. The company plans to inform consumers about the origin and history of the product and its ingredients, either

through a web page or through supplier information on the package.

The producer stated that legal compliance is an important reason as to why they engage in traceability. They also emphasize the importance of being able to quickly follow up on mistakes, such as where in the process a problem has occurred. Another reason is the ability to proudly sell their products and be confident that they measure up to the company policy of selling high-quality products.

Supplier 1 stated that they have experienced an increased desire among consumers for more information about the products, such as origin. Hence, the supplier is now working to refine the traceability to meet this consumer-driven request. Supplier 1 was at the time of the interview soon to launch a traceability system (which is now up and running) where the consumer can see what geographical areas the product comes from and its history from farm to fork through the company website. This is a new approach for the company, where traceability is used to communicate product attributes to the consumers. Before, traceability was used only to ensure food safety and quality. The supplier hopes through this 'communication with the consumer' to develop a closer relation with the consumer through traceability and to generate interest. The supplier also stated that at the end of the day, the goal of making more money has an impact on why they engage in improving their traceability.

Supplier 2 mentioned that the primary objective for which they engage in traceability is not only legal requirements, but also monetary reasons. They want to avoid loss and facilitate follow-ups as organic products are more expensive than conventional ones. Traceability according to the focal company's aim is regarded by supplier 2 as an opportunity and means of gaining a competitive edge by describing their excellence. This is especially true when it comes to industrial products, since suppliers are not normally displayed on or in connection with the final product.

Supplier 3 mentioned an increased demand from the consumers for fair trade and organic products: 'Consumers care about where it comes from and how it is handled'.

Supplier 4 did not usually think in terms of traceability, but when doing so it was primarily as a means to trace products downstream through the best-before-date in case of a recall. When it comes to traceability upstream, the objective is to visualize the origin of the product, and foremost the producer, because that is one of the core values of the company. Supplier 4 also mentioned improved quality but rather as a beneficial outcome than an objective for engaging in traceability.

The distributor, who also warehouses the finished products, states that legal requirements are an important objective, although the company had traceability long before it became a legal stipulation. He mentioned that it was very important for them to have control of product location. But it is also an economical issue, as many of the products are very expensive.

The results from the surveys of the different actors' objectives for engaging in traceability are summarized under three main categories in Figure 2: food safety and quality, managing the SC and internal resources and communication with consumers. These categories are based on the literature study, and the survey was structured according to the same categories.

The survey confirms the results from the interviews that all actors want to engage in traceability. However, they have different priorities for different objectives, as shown in Figure 2. The focal company graded all categories as having the highest priority, while it is clear that the main objectives vary among the actors.

Analysis and Discussion

The interviews and survey results in accordance with the literature reveal that actors in food SCs have different objectives for their engagement in gaining and maintaining traceability[1,6,15–18].

In the literature search, monetary considerations or the ability to charge premium prices due to market differentiation were not explicitly mentioned as reasons for engaging in traceability. However, the distributor, supplier 1 and supplier 2 mentioned monetary reasons in the interviews. Supplier 2 and the distributor connected monetary earnings gained through traceability with the ability to avoid loss and facilitate follow-ups. Supplier 1 regarded it more in general terms to generate financial benefits. The other objectives identified from the interviews and the survey fall into the following three categories.

Food safety and quality

In the survey, all actors in the participating companies agreed or partly agreed that improved food safety and quality was an objective for which they engaged in gaining or maintaining their traceability. Both the focal company and supplier 4 stated in the interview that increased food safety was a beneficial outcome.

According to the literature, legislation[18] can be regarded as a driver for traceability. Legislation was not covered specifically in the survey but was mentioned by three of the actors as an objective. Supplier 2 added that it was their primary objective. Both the producer and supplier 4 found the ability to trace products downstream in case of a recall as an important objective, one which was also found in the literature[16]. This objective certainly relates to food safety in that suppliers do not want consumers to buy or consume food products that are unsafe.

For the focal company, ensuring that the organic products are in fact organic is based on co-operation with KRAV. The ingredients are assumed to be organic as long as the supplier has a valid certificate. This can be related to the legislative aspects, even though it is not clearly expressed as such. Furthermore, this view indicates a link between food quality and safety and the ability to guarantee

the organic origin. As with the focal company, suppliers 1, 2 and 3 also rely on inspections from KRAV to ensure that the organic products supplied to them are organic. Furthermore, the primary producers are not allowed to have parallel production of organic and conventional production according to the KRAV regulations (i.e., the risk of getting conventional products from a primary producer with a valid certificate is considered very low). Supplier 4 also relies on the certification system to ensure that the products supplied meet the guaranteed/labeled attributes (i.e., fair trade and organic). In this respect, the organic certification and non-parallel production increase producer trust that they are being supplied with organic products and are delivering organic products to their consumers. The organic certification can therefore be seen as a quality attribute.

Managing the supply chain and internal resources

Despite the theoretical claim that the traceability system is crucial in finding the most efficient way to produce, assemble, warehouse and distribute products[15,16], the survey and interview results reveal that the participants (apart from the focal company) generally do not regard managing the SC and internal resources as an objective for traceability to the same extent as they regard food safety and quality. The CEO of the focal company, on the other hand, states in the interview that co-operation between the actors in the chain is important for traceability, although she finds that trust between the companies is even more important. Because the products are organic, you have to, above all, trust that the suppliers are doing what they say they are.

Some of the relations in the SC studied are formalized in contracts, whereas others are not. In general, relations with the larger companies are more formalized, whereas those with smaller companies are more based on trust and close co-operation without formal agreements. The interviews indicated that a good customer–supplier relation on which you can build co-operation is important. Agreements formalized in contracts are important although a good relation is even more important. Researchers such as Bowersox et al.[28], Lambert and Cooper[11] and Mentzer et al.[29] state that the competition of today is no longer at the level of company versus company but in SC versus SC, which requires good relationships. Narayanan and Raman[12] state that companies tend to optimize themselves rather than the SC. This means that efforts are needed to get an entire SC to move in the same direction. These efforts can be in the form of contracts, sharing of information and/or trust[12].

Even though all actors in the SC are responsible, it is primarily the focal company's responsibility, as the CEO states, for the overall traceability of their products, since they put the products together. Supplier 1 agrees but emphasizes the importance of all of them contributing. Supplier 4 closely co-operates with their sub-supplier of ingredients to the focal company. The sub-supplier has no production of its own but purchases the raw material from the co-operatives and works with yet another company that processes the raw material into the two ingredients supplied to the focal company. Supplier 4 does not generally supply producing companies with raw ingredients, but has a special arrangement with the focal company in which the products supplied are currently exclusively supplied to them. This testifies to the importance of close relations among the SC actors and that traceability matters in the field of the organic products studied.

For all of the actors studied in general, the relations among them have existed for a long or very long time. Supplier 4 has closely co-operated with its large suppliers and as the number of actors in Europe is limited, they meet each other regularly at different arrangements such as conferences. Most of their suppliers have worked with them for 15–20 years. The relations are not formalized in any contract but rely instead on long trust building. One exception is supplier 3 that has recently contracted a new sub-supplier of the organic product supplied to the focal company. This is different from the established relations in that building on trust requires time and effort, while signing agreements is rather quick.

The CEO notes that for them as a small company it has been hard to establish good relations with retail organizations, which have such large purchasing organizations. The ability to influence other companies in traceability issues is dependent on company size, according the CEO. Small companies are limited in their ability to influence large companies but the CEO states that they do what they can to 'plant the idea'.

Communication with consumers

All the interviewed suppliers and the focal company rely on the certification process to ensure that the products they supply meet the desired organic product attribute (and also fair trade for supplier 4). This relates to the objective and importance of communicating imperceptible attributes to consumers.

Beer[25] claims that the shift in perception of food quality among consumers also includes qualitative aspects related to cultural, environmental and ethical values. This shift is sensed by supplier 1 as an increased desire among consumers for more information about the products, such as knowledge of origin. This is also sensed by supplier 3 as an increased demand for fair trade and organic products. The response to this shift for supplier 1 has been a refinement of their traceability to meet these requests for more information and communicating it to consumers. This is in line with the ambitions of the focal company that wants to 'provide more information to the interested consumer' through traceability. Supplier 1 hopes for a closer relation with the consumer through traceability and to create an interest among consumers through the company's communication of imperceptible attributes such as organic

and origin. In line with this, an important objective for supplier 4 is to communicate to the consumer where the product comes from, but primarily who the producer is since this is one of the core values of the company.

Supplier 3 has the lowest average agreement among the suppliers when it comes to consumer communication as an objective for traceability. This is, however, caused by two sub-issues in the survey: they disagree on market differentiation and partly disagree on certification of authenticity. On the rest of the consumer communication sub-issues, however, they partly agree, which means that they consider consumer communication to be one of their objectives.

Meeting consumer demands for more information on qualitative aspects such as cultural, environmental or ethical values carries associated costs, according to Beer[25], but also provides the SC companies with the opportunity for differentiation and premium prices. As revealed in the interviews, this potential is realized by supplier 1, since they also see a monetary reason behind their investment in refining the traceability to communicate product attributes to the consumers. Consumer communication through traceability is regarded by supplier 2 as an opportunity and means of competition for them. This is especially the case when it comes to industrial products where suppliers are generally not displayed on or in connection with the final product. Communication with consumers is an important objective for the focal company as the brand owner and for the other actors that indirectly benefit from increased sales volume, or if the communication can contribute to making the product a high margin product. However, if the focal company succeeds in reaching its goal of visualizing the SC for consumers and displaying the company names of the suppliers, they would benefit from the communication both indirectly and directly.

Conclusions

Actors in food SCs have different objectives for their engagement in gaining and maintaining food system traceability[1,6,15–18]. These objectives can be divided into three categories: food safety and quality, SC management and internal resources and communicating with consumers. The different objectives among actors were confirmed by the survey conducted with the companies participating in the study.

The EC Food Safety Regulation 178/2002 can be regarded as a baseline that safeguards a certain level of food safety. However, as consumer awareness increases, driven by food scares and scandals, focus has been placed not only on using traceability to achieve food safety but to address consumer concerns regarding product and process characteristics, such as the imperceptible organic attribute.

Thus, for an SC to succeed in communicating imperceptible product and/or process characteristics to the consumer, enhanced traceability is required[3]. This requires, in turn, co-operation among the actors in the SC regarding the physical and informational flows in the chain. This SC perspective was not regarded as the main objective for the actors in this study, except in the focal company. In order to move forward, relational aspects such as trust among actors are equally important to information and physical flow. For small actors trust is the key, as they rely on each other without formal agreements and on the certification process for ensuring the desired product attributes, which is organic in this case.

A suggestion for further research is the ability to include demands regarding traceability breadth (amount of information), depth (how far back and forward in the SC) and precision [resolution, size of the traceable resource unit (TRU)] in the supplier evaluation and screening. This will safeguard that the information recorded by the suppliers enables the breadth, depth and precision of traceability required by the focal company to ensure and to communicate desired imperceptible product attributes.

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Farmer-developed vegetable intercropping systems in southern Hebei, China

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Abstract

The expansion of intensive vegetable production systems exacerbates ongoing resource degradation in China's Hebei province. There is an urgent need to develop and disseminate more sustainable vegetable production systems. Intercropping, the simultaneous cultivation of two or more crops on the same field, is widely practiced in the region. Intercropping can use environmental resources more efficiently and is therefore considered to generate high and stable yields with lower inputs. Until now, scientific literature on vegetable intercropping in China is non-existent. To identify prevailing vegetable intercropping systems, a qualitative inquiry was conducted in southern Hebei province. Researchers, extensionists and farmers were interviewed on the occurrence, methods, potentials and constraints of vegetable intercropping. Furthermore, semi-structured in-depth interviews were conducted to examine the farmers' underlying motives and concepts and to determine the origin and distribution of the systems. The investigations revealed a huge variety of sophisticated systems being practiced in southern Hebei. Apart from pure vegetable intercropping systems such as spinach–garlic, especially maize–vegetable and cotton–vegetable systems are widespread. The systems are developed by the farmers themselves and disseminated by the state extension service. Apart from the benefits of plant health, the optimal use of limited land resources is the main reason for farmers to exercise intercropping. However, with the ongoing mechanization and labor force reduction in the agricultural sector, a great part of the intercropping systems, which demand a high input of manual labor, are prone to extinction in the long run. Recent research in China focused purely on agronomic advantages of intercropping, neglecting the linkages between the socio-economic developments and farmers' decisions in the field. To overcome this dilemma and to maintain the traditional and sustainable intercropping systems, we conclude that only an integrative research approach that involves various stakeholders from the beginning is able to adjust the intercropping systems to future demands.

Key words: intercropping, vegetables, knowledge transfer, adoption, Hebei, China

Introduction

For many years, food security along with that of grain self-sufficiency had been the major goals of China's agricultural policy. In the course of the transformation process, land use rights returned to farmers, price liberalization took place and the grain procurement quota was abolished[1]. This led to a steady change of cropping systems, with a remarkable shift in the production of high-value crops such as fruits and vegetables. In Hebei province, the production of vegetables increased from 30 million tons in 1997 to 63 million tons in 2007. As the production of vegetables generates higher income possibilities to the rural population, it is an important option for reducing the ever widening rural–urban income gap.

The North China Plain is East Asia's largest alluvial plain, accounting for one-fifth of China's total food production[2,3]. The farming structure is dominated by smallholders with approximately 0.5 ha of arable land[4]. High production intensities ensured steadily increasing yields over the past few decades. However, this has mainly been achieved by increased inputs of fertilizer, irrigation and plant protection[4]. Consequently, negative impacts on the environment and resource availability are aggravating. Ongoing contamination and depletion of water resources and degradation of arable land severely compromise the production base for future generations[5–9].

Southern Hebei province is located at the center of the North China Plain. The climate is a continental monsoon climate with average temperatures ranging from below zero

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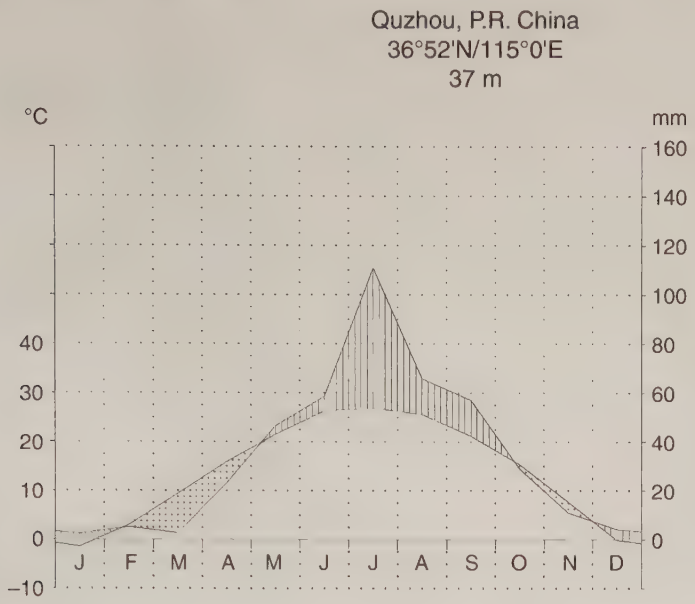

Month	Temp. (°C)	Prcp. (mm)
Jan	−1.4	2.4
Feb	3.0	5.2
Mar	9.4	2.7
Apr	15.9	23.1
May	21.5	46.5
Jun	26.3	58.6
Jul	26.9	110.9
Aug	25.6	65.8
Sep	21.2	57.1
Oct	15.4	29.0
Nov	7.7	11.0
Dec	−0.1	4.2

Annual mean temp. 14.3 °C

Total Annual Prcp. 416.5 mm

Figure 1. Climate graph of Quzhou Experimental Station, Handan city region, Hebei; based on daily data from 2001 to 2009.

in January to 27°C between June and August. Annual rainfall ranges from 300 to 700 mm with most precipitation in the summer months[10]. Due to the arid conditions between October and April (Fig. 1), irrigation is mandatory to extend the cropping season. Major crops are wheat, maize, cotton and, increasingly, fruits and vegetables[11].

Intercropping, the simultaneous cultivation of two or more crops on the same field, is a traditional system in the North China Plain[12–14]. According to various studies, intercropping can use environmental resources more efficiently. When cultivating two crops in a mixture, the variation in the canopy structure and rooting patterns can facilitate a better capture of solar radiation, soil nutrients and soil water[15,16]. Therefore, intercropping can lead to higher yields[17] and at the same time groundwater pollution can be minimized by the control of nutrient leaching[18]. Due to the often improved ground cover, weed pressure is reduced[19–21] and erosion can be controlled[22]. Pest and disease pressure can be reduced in intercropping, as the companion crop can offer a habitat for parasitoids or might have a repellent effect on certain pests[23]. Therefore, intercropping of vegetables is promising to provide farmers' incomes and at the same time save environmental resources.

In the past decade, intercropping became a big issue in agricultural research in China. Different research groups examined various intercropping systems from an agronomic point of view. The focus was mainly on nutrient use efficiency and yield components in grain and grain–legume systems in the North China Plain[24–26]. The findings confirm the positive effects of intercropping regarding yield, resource use and environmental aspects. However, vegetable intercropping systems have so far been neglected by research.

Another aspect that has not been taken notice of is the adoption of these potentially sustainable and high yielding production systems by local farmers. Experience shows that it is still a major issue to bridge the gap between theory and practice in sustainability research[27,28]. Production techniques that proved successful in experiments do not necessarily work out in the field. The socio-economic framework and socio-technological regimes farmers are acting in are often insufficiently considered. Furthermore, under changing frame conditions, traditional production systems run the risk of extinction[29].

To maintain the potentially sustainable vegetable intercropping systems in the North China Plain and to be able to adjust them to a permanently changing environment, it is essential to understand farmers' underlying motives and concepts. Therefore, the present study reveals what kind of vegetable intercropping systems are practiced as well as how and why farmers do or do not practice intercropping. By assessing past developments and recent changes in the socio-economic framework farmers in Hebei are exposed to, the future potential of certain systems is evaluated and suggestions are given on how to adjust them to suit upcoming demands.

Materials and Methods

The main goal of the present study is to create an overview on the existing intercropping systems in southern Hebei province, with a special focus on vegetable intercropping practices. Due to the complete lack of literature and data on vegetable intercropping in the region, a qualitative inquiry was conducted. Stakeholders involved in developing, disseminating and practicing vegetable intercropping were included in the survey. Local farmers, employees of the state extension service from the local to the provincial level and agricultural researchers, who are engaged in

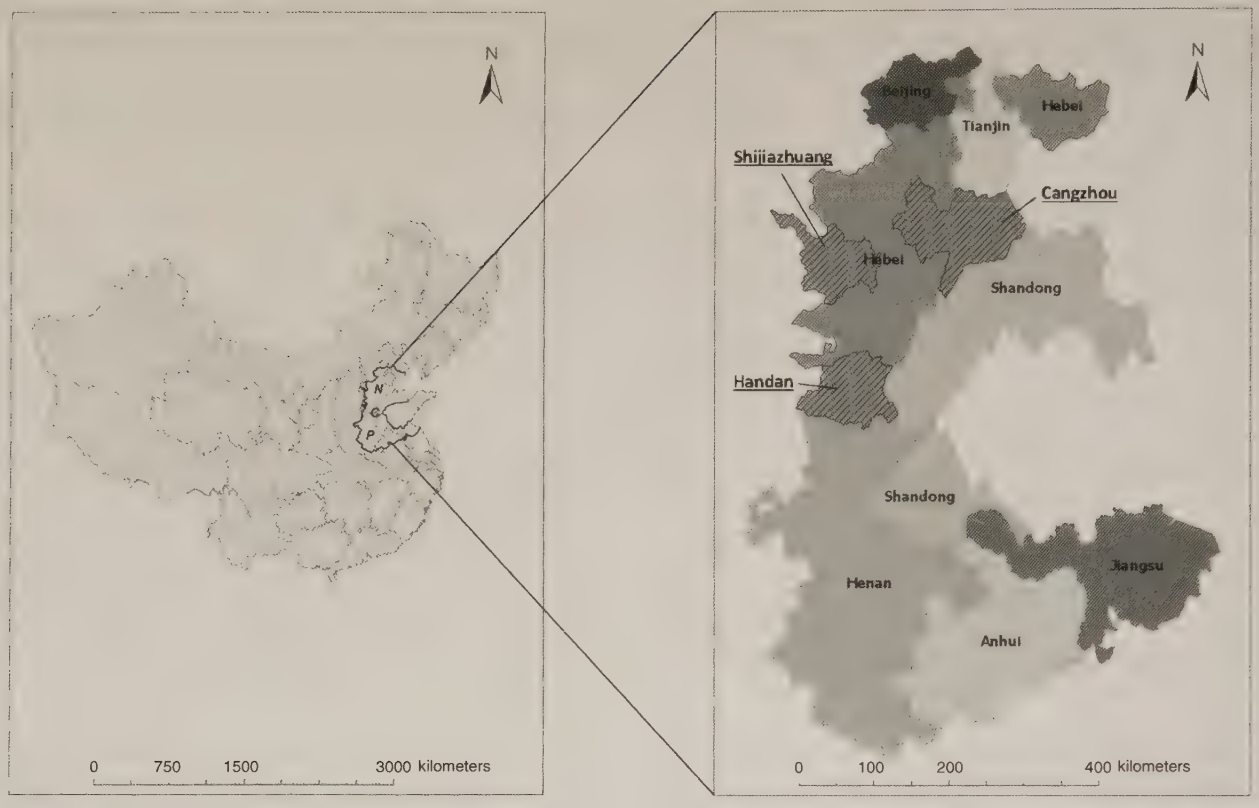

Figure 2. The North China Plain in mainland China (left) and the location of the surveyed city regions in Hebei province and the North China Plain (right).

intercropping research, were interviewed. The following were the specific objectives of the inquiry: (1) to identify and characterize prevailing intercropping systems, especially vegetable intercropping systems in the region; (2) to understand factors influencing the dissemination and adoption of vegetable intercropping; (3) to understand the farmers' knowledge, awareness and perception of different intercropping components; (4) to assess the future potential and constraints of vegetable intercropping systems (i.e., the necessity for and possibility of mechanization); (5) to identify demand for future research. Semi-structured in-depth interviews were conducted[30]. The farmers' questionnaires consisted of 25 questions, whereas the questionnaire for researchers and extensionists consisted of 28 questions. The farmers' questionnaire focused on the agronomic details of the practiced intercropping system, the individual's intercropping history, perceived benefits and drawbacks of the system and on the awareness of environmental connectivity. Additionally, the interviews with researchers and extensionists inquired on a meso- and macro-level, addressing the generation and transfer of research findings as well as the perception of the farmers' knowledge and motives. As the goal of the study was to obtain the greatest possible information from the cases in the sample, snowball sampling[31] was applied.

The survey was conducted in the Cangzhou, Handan and Shijiazhuang regions (Fig. 2) from October 2007 to April 2008 with the help of a previously trained interpreter. In total, 35 farmers (21 intercropping, 14 non-intercropping), ten extensionists and six researchers were interviewed. All interviews were recorded, translated and transcribed into English, according to the transcription guidelines of McLellan et al.[32], while the analysis was done drawing on the content[33]. Additionally, data from provincial and national yearbooks were consulted to understand and describe the changes in the frame conditions for rural farm households in Hebei. Due to the vastness of the surveyed region, with some 5 million farmers[4], the scope of the inquiry was neither to determine the share of intercropping among all cropping systems nor to determine the share of certain intercropping systems among the entire intercropped area. However, the area under cultivation of a certain intercropping system in the surveyed counties, as reported by the local farmers and extension service, is displayed.

Results and Discussion

Existing intercropping systems

A huge variety of intercropping systems exist in southern Hebei province. In Table 1, the most common systems and the crops used in the systems are categorized.

As most intercropped species differ highly in their growing period, only in the case of spinach–garlic (Fig. 3A), maize–chili (see Fig. 6), maize–peanut and maize–soybean

Table 1. Common intercropping systems and crop combinations in southern Hebei province.

Intercropping systems	Explanation	Crop combinations
Real intercropping	Crops grown simultaneously; most of their growth period is in the same field	Two vegetables, maize–peanut, maize–soybean, maize–vegetables
Relay intercropping	Certain part of crops' growth period is in the same field (2–6 weeks)	Maize–wheat, maize–vegetables, wheat–vegetables
Unconscious strip intercropping	Small plot sizes create strips of different crops in neighboring fields	Various crops
Field border intercropping	Fields are fenced with different crops	Various field crops fenced by: millet, trees, sunflower, vegetables
Agroforestry	Annual crop grown under perennial crop	With poplar and fruit trees: wheat, cotton, maize, sunflower, sesame, vegetables
Multi-layer intercropping	Three or more crops of different canopy height grown in the same field	Maize–different vegetables, poplar–sunflower–cotton, poplar–cotton–sesame

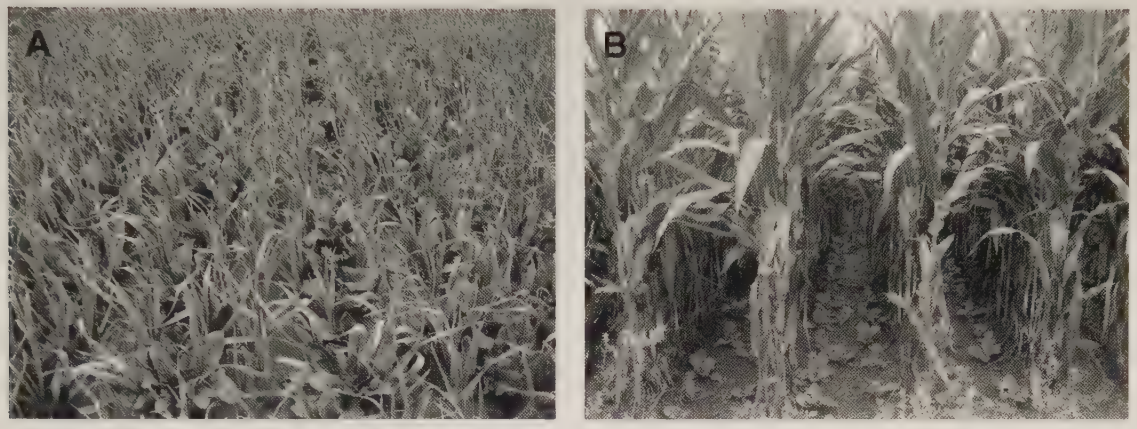

Figure 3. Real intercropping of spinach with garlic (A) and relay intercropping of maize with Chinese cabbage (B).

does the definition of intercropping, 'two crops being cultivated most of their growing period together in the same field', hold true. In relay systems, the intercropped components only share parts of their growing period. This is especially the case in most maize–vegetable systems, where the vegetable components have a much shorter growing period. Due to the high average temperature of just below 30°C between June and August, the production of leafy vegetables is restricted to spring and autumn. If farmers want to combine the production of leafy vegetables with the production of maize, relay intercropping is a suitable option (Fig. 3B).

The case of unconscious strip intercropping happens, due to the given small plot sizes in the North China Plain. Most farm households in southern Hebei province cultivate less than half a hectare[4]. On an average, each household cultivates more than five plots with an average plot size of 0.07 ha[34]. The extreme land fragmentation happened in the course of the implementation of the household responsibility system. The land within each village, which had been cultivated collectively before, was classified according to quality and then allocated equally among farm households[35,36]. As a consequence, it often occurs that farmers grow different crops in neighboring fields. The crops of the neighboring plots influence each other above and below the ground, especially in the rows near the neighboring crop, and can thus be considered as intercropping.

Field border intercropping (Fig. 4), the fencing of fields with various crops, is a common practice all over the region. The fencing crop indicates the boarder to the neighbors' fields in vast monocropping areas, while at the same time it supplies an additional food stock for home consumption.

Agroforestry systems have increased tremendously in recent years (Fig. 5). The main reason is a government policy, which encourages farmers to plant 10–50 m strips of trees along all major roads throughout the country. The main goal is to counteract the deforestation of the past few decades and at the same time cover future timber demand. Farmers make use of the land between the trees for the next 2–3 years, until light absorption by the trees' canopies impedes satisfying yields of the understory crops. Similar practices can be observed in young orchards, where farmers plant vegetables in-between rows of fruit trees.

Vegetable intercropping systems

In the following section, two vegetable intercropping systems of southern Hebei province are described in detail. The two systems were selected as they are of growing

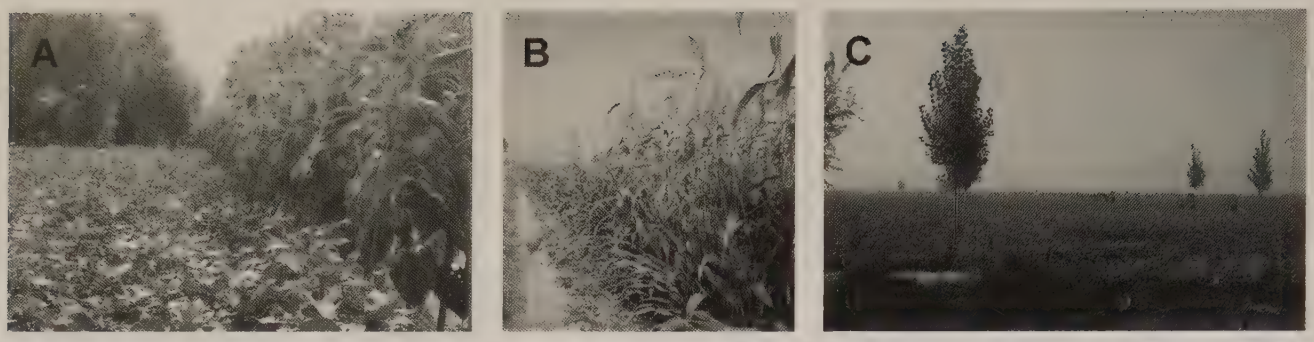

Figure 4. Examples of field border intercropping. (A) Cotton field fenced by sunflower. (B) Maize field fenced by a row of millet and Chinese cabbage. (C) Cotton fields fenced by poplar and sunflower.

Figure 5. Examples of tree–crop intercropping systems. (A) Poplar with cotton and maize. (B) Poplar with various vegetables. (C) Cherry with cauliflower.

importance, with the area under cultivation increasing steadily in recent years.

Chili–maize intercropping. In the Cangzhou county (Cangzhou region), farmers intercrop chili with maize on approximately 750 ha. Chili seedlings are planted at a four-leaf stage into the plastic mulched soil in the beginning of April and harvested from the middle to the end of October. Maize is sown in May and harvested at the end of August. Irrigation is applied in spring according to demand. The system yields 4.5 tons of dried chili and 5 tons of maize cobs. Farmers report that pest and disease pressure are reduced in the intercropped chili, compared to the monocropped plants. High quality chili has to be free from the visible damage caused by pests and be unaffected by rotting or any other deterioration. Additionally, threshold values for pesticide residue concentrations have to be compiled. These standards are more easily fulfilled by the intercropped chili, which can thus generate higher returns. A sketch of the spatial arrangement in the field is given in Figure 6.

Onion–cotton relay intercropping. A vegetable-relay-intercropping system of onion–cotton is practiced in the Feixiang county (Handan region), comprising approximately 550 ha. Onion is planted in the middle of October and grown over winter. One month before the harvest of onion, around the 25th of April, cotton is sown directly in double rows between four rows of onion. For both crops plastic mulching is applied. Therefore, weed control measures are reduced to the crop-free strips. During winter, the low soil temperature in the unmulched cotton strip impedes severe weed infestation. In spring, the cotton strip is tilled by a hand hoe or two-wheel rotary tiller. This prepares the seedbed and at the same time emerging weeds are controlled. After the harvest of onion, cotton is grown in a monoculture. Before cotton canopy closure, mechanical weed control is repeated according to the demand. Cotton harvest starts in the middle of August and ends in the beginning of October. Farmers harvest approximately 8 tons of onion and 4.5 tons of seed cotton. A scheme of the spatial arrangement of this system is shown in Figure 7.

Farmers' motives

The most important factor that convinces farmers to practice intercropping is to make full use of space and thus achieve a higher income from their limited land resources, as stated by all interviewed farmers. In the case of the chili–maize system, 'protection of vegetables by the maize' plays the major role. Farmers experience reduced pest and disease pressure on chili in the intercropping system. They can produce higher quality (i.e., free of visual damage and lower pesticide residues), and at the same time reduce inputs for plant protection. The often stated advantage of intercropping 'avoidance of crop failure'[37,38] was never mentioned by the interviewees. This might be due to two reasons. First, the farming structure in the region is already highly diversified. As a result of the small scattered land, farmers tend to cultivate different crops in different plots. Thus, the argument for intercropping, of

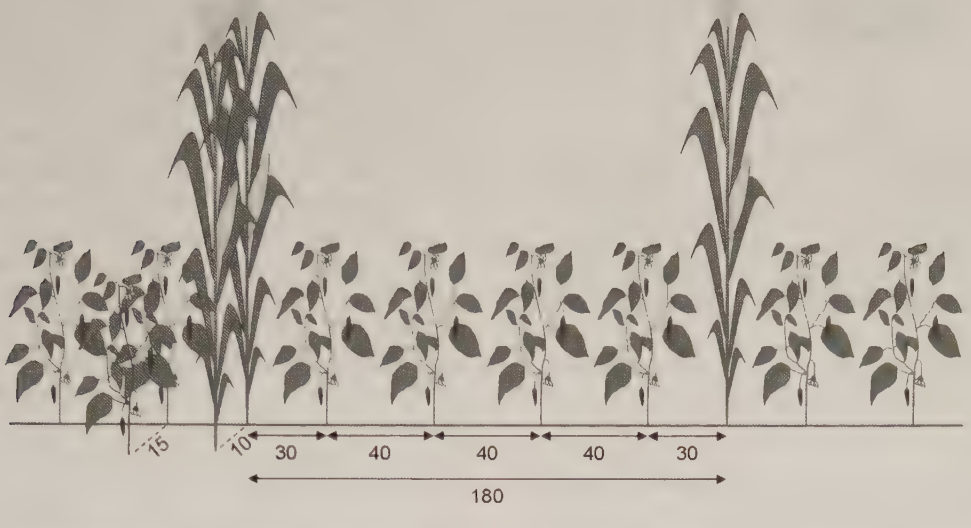

Figure 6. Spatial arrangement of chili–maize intercropping middle of August. Distances between plant rows and single plants, respectively, are given in centimeters.

Figure 7. Spatial arrangements of onion–cotton relay intercropping just before harvest of onion, end of May. Distances between single rows and plants, respectively, are given in centimeters.

being on the safe side in case of crop failure, is besides the point. Second, the supply and application of farming inputs, especially pesticides, fertilizer and irrigation water, is ensured and has steadily increased over the past few decades[39]. As a consequence, the risk of crop failure due to drought, lack of nutrients or pest and disease is negligible. Another strong argument for intercropping, its potential environmental benefit, is not considered by the Chinese farmers. Only very few farmers showed some awareness of connectivity between their cropping activities (use of pesticides, fertilizer and irrigation) and the possible effects on ground water and thus human health. However, all interviewed extension staff (and researchers) stated that intercropping has certain potential to counteract environmental pollution.

When talking about the drawbacks of intercropping, one has to distinguish between farmers experienced in intercropping and those who never practiced intercropping. A higher labor input required along with the inconvenience of management is reported by all farmers who practice intercropping. Sowing or planting of a second crop into an already established stand of another crop is difficult. Additionally, one has to be very cautious during harvest in systems with two crops of different harvest periods. In case of the onion–cotton relay intercropping, discussions with the local state extension service were ongoing on adjusting the system to enable mechanized mulching and sowing of cotton.

Farmers who so far had not been involved in intercropping stated a 'lack of cash' as one reason why they never practiced intercropping. Limited financial resources restricted the purchase of two kinds of seeds. The main reason, however, is that farmers simply had never heard of intercropping.

The factors influencing the distribution of intercropping can be summarized as follows. Pressure on land resources is highly influenced by the available land resources per farm household and the extent of off-farm income possibilities. Intercropping is more widespread in remote rural areas compared to suburban areas, where farm households can generate greater parts of their income in the non-agricultural sectors. Looking at the systems itself, the possibility of mechanization plays an important role, and, with the steadily increasing use of machinery[4], will become

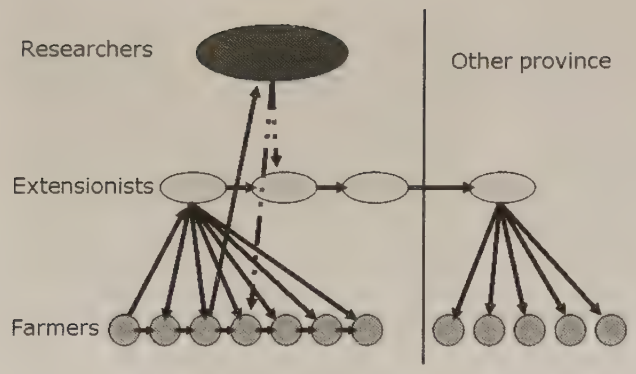

Figure 8. Schematic description of knowledge transfer of intercropping in southern Hebei.

a key issue for the future of intercropping in the region. Tradition and knowledge, along with that of the role of extension, also have a strong influence on the distribution.

Knowledge transfer

As reported in all examined cases, the intercropping systems have been developed by the farmers themselves or their ancestors. Successful systems are then picked up by neighbors, relatives and other farmers in the village. According to farmers and extensionists, the dissemination on a larger scale is accomplished by the state extension service. After testing and improving, promising systems are redistributed to farmers in the region and also passed on to other extension agents at regional and provincial levels. Due to its interesting features, various intercropping systems have been examined by agricultural researchers. However, generated knowledge is rarely reverted to the extension service or farmers directly (Fig. 8). Extension agents claim that researchers would not know about the farmers' problems and keep the results in their laboratories. On the other hand, researchers state that extension staff are often not well trained in the field of agriculture and should be re-educated. For the development and distribution of sustainable production systems, another fact has a crucial impact. The implementation of a series of self-sufficiency reforms encouraged the agricultural extension service to generate at least parts of their budgets through commercial activities[40]. Employees of the state extension service are often involved in the trading of fertilizer, pesticides and other farm inputs[41]. Therefore, their interest in promoting input-saving production systems such as intercropping is small. A wide adoption of such systems among farmers would decrease their sales and income directly.

Future of intercropping

In the beginning of the 1990s, one-third of all grains in the North China Plain were produced in intercropping systems[42]. When comparing the observations in our survey, it becomes obvious that the intercropping area has been greatly reduced in the past two decades. The question arises, whether this trend is going to continue in the future and what are the reasons behind it. Therefore, we link the findings of the inquiry with the developments of the socio-economic frame conditions over the past few decades.

As discovered during the inquiry, the future potential of intercropping is perceived differently by farmers, extensionists and researchers. Farmers practicing intercropping are often very confident about their systems and predict that the area under cultivation is going to increase in the near future. On the contrary, a great share of the interviewed extensionists wonder whether intercropping as a traditional system can be combined successfully with the demands of modern agriculture. All researchers recognize the potential of intercropping as a more sustainable production system. However, skepticism prevails as to whether intercropping can be disseminated on a large scale.

Assessing the future developments regarding certain types of intercropping, we can say that the area of unconscious strip intercropping is going to reduce slowly but steadily. Between 1986 and 1990, the average plot size decreased from 0.08 to 0.07 ha[34]. However, since then, land consolidation has been put on the agenda and set as an urgent task in the 'eleventh five year plan' of the state council of the People's Republic of China[36]. Even though radical changes in the land consolidation policy are unlikely to happen, especially with the current system of land allocation at the village level[35], land fragmentation is considered to reduce steadily in the next few decades[43]. As a consequence of larger fields, field border intercropping is also going to diminish.

The major driving force changing the agricultural production systems in Hebei and the whole of China is the increasing use of machinery. The number of agricultural tractors in Hebei province increased from 0.3 million in 1985 and 0.9 million in 1995 to 1.6 million in 2007[4]. At the same time, the labor force in the agricultural sector and the dependency on income from agriculture is decreasing. In Hebei province, the number of agricultural laborers decreased from nearly 18 million in 1990 to less than 15 million in 2007[4]. On a national basis, the share of income from agriculture fell from 82.4% in 1990 to 68.3% in 2005[44]. As both trends are most likely to continue, systems that demand a large share of manual labor are going to diminish. Efforts are already underway to develop systems that maintain the advantages of intercropping in a mechanized system. Strip systems adjusted to the working width of the machinery in use might increase in the future. Certainly, vegetable production is less exposed to the pressure of mechanization, since in 'modern' agricultural systems a great share of vegetable production is still harvested by hand. Therefore, the arrangement of the vegetable component in intercropping systems is going to be less affected by this trend.

With the increasing opportunity costs for labor, the economics of intercropping systems in rural China have to be reconsidered. In the past, farmers hardly set any price for their invested labor. If the two-component crops in the

intercropping system produced a higher yield compared to their monocropping equivalents, the system seemed more profitable to the farmer ignoring the increased input of labor. Nowadays, farmers are becoming more and more aware that higher labor input has to be overcompensated by a higher gross margin. Reduced pest and disease pressure not only reduces expenditures on pesticide inputs, but also offers the opportunity to receive a significantly higher sales price for higher quality produce, as is the case in the chili–maize system. Increased fertilizer and irrigation water use efficiency in intercropping[15,16,24–26] can contribute additionally to its profitability[45]. This point becomes even more important with the ongoing advances in agricultural and environmental policy-making in China. The development of water pricing systems[46] and the establishment of payments for environmental services such as the 'grain for green' program[47] could directly or indirectly increase the returns of intercropping systems.

Conclusions

A huge variety of sophisticated vegetable intercropping systems implemented by farmers was identified in southern Hebei province. Apart from the beneficial effects of plant health and product quality (chili–maize system), the fact that rural farm households often have to generate all income from their limited land resources explains the development and widespread practice of these labor-intensive intercropping systems. There is strong evidence that most traditional intercropping systems, which depend on high inputs of manual labor, are going to reduce steadily in the course of the economic development and increased mechanization of agriculture. Thus, the potential benefits that are connected with intercropping are also likely to disappear. To maintain intercropping and the associated potential to counteract environmental degradation, a new research approach has to be developed. After the first very important step of identifying the yield potential and positive effects of certain intercropping systems on the environment[24–26], research has to focus on the applicability of systems and its adjustment to future demands. Therefore, research should not only focus on one particular aspect of intercropping but also has to integrate multiple disciplinary perspectives. An agronomic and environmental assessment has to go along with the testing of appropriate machinery and economic evaluation of certain systems. Only systems that fit the farmers' requirements will be able to considerably benefit the environment. A transdisciplinary research approach, which involves farmers and the extension service right from the start, seems most promising in this context. Hence, improved communication between all stakeholders is a precondition. Finally, one important point that severely counteracts sustainable development in China's agricultural sector in general has to be revised. The dependency of extension agents on income from farm input sales has to be overcome, to create a real interest in input saving systems such as intercropping.

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Increased weed diversity, density and above-ground biomass in long-term organic crop rotations

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Abstract

While weed management is consistently a top priority among farmers, there is also growing concern for the conservation of biodiversity. Maintaining diverse weed communities below bioeconomic thresholds may provide ecosystem services for the crop and the surrounding ecosystem. This study was conducted to determine if weed diversity, density and biomass differ within and among organic and conventional crop rotations. In 2007 and 2008, we sampled weed communities in four long-term crop rotations near Mead, Nebraska using seedbank analyses (elutriation and greenhouse emergence) and above-ground biomass sampling. Two conventional crop rotations consisted of a corn (*Zea mays*) or sorghum (*Sorghum bicolor*)–soybean (*Glycine max*)–sorghum or corn–soybean sequence and a diversified corn or sorghum–sorghum or corn–soybean–wheat (*Triticum aestivum*) sequence. Two organic rotations consisted of an animal manure-based soybean–corn or sorghum–soybean–wheat sequence and a green manure-based alfalfa (*Medicago sativa*)–alfalfa–corn or sorghum–wheat sequence. Species diversity of the weed seedbank and the above-ground weed community, as determined by the Shannon diversity index, were greatest in the organic green manure rotation. Averaged across all sampling methods and years, the weed diversity index of the organic green manure rotation was 1.07, followed by the organic animal manure (0.78), diversified conventional (0.76) and conventional (0.66) rotations. The broadleaf weed seedbank density in the tillage layer of the organic animal manure rotation was 1.4×, 3.1× and 5.1× greater than the organic green manure, diversified conventional and conventional rotations, respectively. The grass weed seedbank density in the tillage layer of the organic green manure rotation was 2.0×, 6.1× and 6.4× greater than the organic animal manure, diversified conventional and conventional rotations, respectively. The above-ground weed biomass was generally greatest in the organic rotations. The broadleaf weed biomass in sorghum and wheat did not differ between organic and conventional rotations (CRs), but grass weed biomass was greater in organic compared to CRs for all crops. The above-ground weed biomass did not differ within CRs, and within organic rotations the grass weed biomass was generally greatest in the organic green manure rotation. The weed seedbank and above-ground weed communities that have accumulated in these rotations throughout the experiment suggest a need for greater management in long-term organic rotations that primarily include annual crops. However, results suggest that including a perennial forage crop in organic rotations may reduce broadleaf weed seedbank populations and increase weed diversity.

Key words: weed seedbank, biodiversity, long-term crop rotations, organic farming, animal manure, perennial forage

Introduction

Weeds directly compete with crop yield in agricultural systems; thus, weed management is consistently a top priority among farmers. Despite centuries of eradication efforts, weed communities remain viable across the agricultural landscape. Therefore, if weed communities cannot be completely eliminated from the agroecosystem, it may be useful to address the potential utility of those weed communities. Biodiversity has been shown to provide many ecosystem services; thus, increasing the biodiversity of the weed community may provide significant benefits to the

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crop and surrounding ecosystems. These benefits might include: improvement of soil chemical, physical and biological characteristics[1], improvement of habitat for beneficial insects and natural enemies of weeds[2] and reduced soil erosion and chemical runoff[3]. Moreover, a diverse weed community may prevent the rapid accumulation of a single weedy species, due to interspecific competitive interactions. Modern agricultural practices have led to a decline in the diversity of weeds in agroecosystems due to widespread use of herbicides and simplicity of crop rotations[4,5]. Herbicide use reduces weed species diversity[6–9], whereas crop species diversity promotes weed species diversity[10]. This suggests that complex crop rotations may lead to an increase in weed diversity[5]. Organic agricultural certification prohibits the use of synthetic herbicides and requires the use of soil-building crop rotations[11]. As a result, many now view organic agriculture as a means of protecting biodiversity within agroecosystems.

Biodiversity can be measured using two components: species richness and species evenness. Species richness is the total number of species in a given ecosystem and species evenness is the relative proportion of each species in the ecosystem[12]. A diverse community maintains high species richness and high species evenness. There are several methods for measuring weed density and diversity. The above-ground weed population sampling is a common method for quantifying current weed communities, and recent studies have demonstrated an increase in the diversity of the weed community in organic systems using this method[13–17]. Seedbank sampling is another method used to quantify weed communities, but is different as it characterizes the past, present and future of the weed community for a given agricultural field. Seedbanks act as the 'memory' of a weed community, because many weed seeds persist in the soil for more than one year, and may not represent the total or potential above-ground community in a particular year[18,19]. The longevity of many weed species in the seedbank contributes to the 'buffering effect' of the seedbank community[20]. Despite the above-ground management practices, the seedbank acts as a reservoir of biodiversity for arable weed species due to this buffering effect[21]. Overall, the weed seedbank is a better indicator of weed pressure than the above-ground measurements of population[22]. The weed stand will vary by year depending on the weather, whereas the weed seedbank is relatively less sensitive to year-to-year differences in weed population, and can reflect the interaction of weeds and management strategies over time. The increase of weed diversity in organic systems has also been demonstrated using the weed seedbank sampling methodology[9].

The diversity of the weed seedbank may not always correlate to the diversity of the above-ground weed community. In a previous study, the total weed biomass and the above-ground diversity were greater in an organic system compared to conventional, but weed seedbank species diversity was lower in the organic system[17]. The persistence of a few dominant weed species in the seedbank may artificially drive weed species evenness lower, leading to an overall decrease in the weed seedbank species diversity[23,24]. However, weed management practices often prevent the domination of one weed species in the above-ground weed community, resulting in increased weed species evenness in the standing community[25]. If dominant weed species are not managed, organic agriculture may not be a viable solution for the maintenance of biodiversity in agroecosystems. If dominant weed species are managed, one could expect the weed seedbank and the above-ground diversity to be greatest in organic systems, due to the complexity of crop rotations[5] and least in conventional systems, due to the intensive use of herbicides[6–9]. While the relationship between organic cropping systems and weed diversity has been well established in the above-ground weed community, fewer studies have examined this relationship in the weed seedbank community of long-term crop rotations.

Crop rotation, weed density management and nutrient inputs may also have an effect on the weed seedbank diversity and relative quantity of grass and broadleaf species within a system. Grass and broadleaf weed populations are often related to the growth habit, phenology and morphology of the different crops in rotation[9,26,27]. A rotation that includes perennial forage such as alfalfa favors grass weed species and winter annuals that can withstand multiple cuttings, and in turn reduces the population of summer annual broadleaf weeds[28–31]. The source of nutrient enrichment in a rotation may also influence the composition of the weed community. Menalled *et al.*[32] observed a 64% increase in waterhemp (*Amaranthus rudis*, a broadleaf weed species) biomass, due to the application of composted swine manure compared to the no-compost control. Therefore, the complexity of the rotation, the individual crops in rotation and the form of nutrient enrichment (e.g., animal manure, green manure and synthetic fertilizer) all may influence the weed community. Understanding the factors that influence weed communities in long-term crop rotations will be especially useful to organic farmers, who consistently rank weed management as the most important research priority[33,34].

The objective of this study was to evaluate weed seedbank density, weed species richness, evenness and diversity, along with the above-ground grass and broadleaf weed abundance and broadleaf weed diversity, within and among organic and conventional crop rotations. We hypothesized that (1) weed species richness, evenness, diversity, density and above-ground biomass will each be greatest in the organic crop rotations and (2) within organic and conventional crop rotations, the species richness, evenness and diversity will increase and weed density and above-ground biomass will decrease as the diversity of the rotation and management system increases. The results of this study will generate insights useful for designing appropriate crop rotations and weed management strategies that aim to minimize weed density and above-ground biomass while increasing biodiversity.

Table 1. Rotational sequences for each management treatment in the Long-Term Crop Rotation experiment at the University of Nebraska Agricultural Research and Development Center near Mead, Nebraska. The experiment was initiated in 1975 and the crop rotation sequences indicated were initiated in 1996: conventional rotation (CR), diversified conventional rotation (DIR), organic animal manure rotation (OAM) and organic green manure rotation (OGM). The 2007 season concluded the third cycle of the current rotation sequences.

Treatment	Sequence	1st year	2nd year	3rd year	4th year
CR	1	Corn	Soybean	Sorghum	Soybean
	2	Sorghum	Soybean	Corn	Soybean
DIR	1	Corn	Sorghum	Soybean	Wheat
	2	Sorghum	Corn	Soybean	Wheat
OAM	1	Soybean	Corn	Soybean	Wheat
	2	Soybean	Sorghum	Soybean	Wheat
OGM	1	Alfalfa	Alfalfa	Corn	Wheat
	2	Alfalfa	Alfalfa	Sorghum	Wheat

Materials and Methods

Cropping systems

A long-term crop rotation experiment was conducted at the University of Nebraska Agricultural Research and Development Center near Mead, Nebraska, USA. It was initiated in 1975 and redesigned in 1996 to evaluate the productivity of organic and conventional rotations (CRs) that differed in crop rotational diversity, weed management and nutrient inputs. The dominant soil type at the site is a Sharpsburg silty clay loam (fine, smectitic, mesic typic Argiudoll) with 0–5% slopes[35]. The total area of the experiment is 4 ha and fields have been managed without irrigation since initiation.

The experiment was designed as a split-plot randomized complete block with four replicate blocks and 13 experimental units (whole plots) per block. Whole plot treatments in this study consisted of management treatments within crop rotations, which are appropriate for long-term cropping systems research[36]. Treatments within a block included four management treatments: CR, diversified conventional rotation (DIR), organic animal manure rotation (OAM) and organic green manure rotation (OGM). These four management treatments were established in 1996. While the organic treatments were not certified, they have been managed according to Organic Crop Improvement Association (OCIA, Lincoln, Nebraska, USA) certification guidelines since 1996. From 1975 to 1995, previous treatments at this site included continuous corn with synthetic fertilizer and herbicides (HFI CC), a 4-year rotation with synthetic fertilizer and herbicide inputs (HF), a 4-year rotation with manure only (ORG) and a 4-year rotation with only synthetic fertilizer inputs (FO). In 1996, the HFI CC treatment was converted to CR, the HF converted to DIR, the ORG was renamed the OAM treatment (but did not change in practice) and the FO was converted to OGM. A panel of local farmers was consulted in the design and management of crop rotations at the onset of the experiment, and prior to the changes in 1996. Thus, the rotations in this experiment include crops and management practices typical to eastern Nebraska.

The current DIR, OAM and OGM treatments were each replicated four times within each block so that each entry point of the 4-year crop sequence was present each year within each block. The CR treatment is present in only one experimental unit per block; therefore, each entry point of its 4-year crop cycle is not represented in each block. Each whole-plot experimental unit in the study was 0.047 ha (12.2 m × 38.4 m). Split-plots were created in 1996 resulting in two crop rotation sequences within each whole-plot management treatment. The split-plot sequences were added to include sorghum in the corn phase of each rotation.

Detailed crop sequences for the four management treatments are summarized in Table 1. The CR treatment was maintained in a corn–soybean–sorghum–soybean (sequence 1) or sorghum–soybean–corn–soybean (sequence 2) rotation with synthetic fertilizer, herbicides and mechanical tillage. The DIR treatment was in a corn–sorghum–soybean–winter wheat rotation (sequence 1) or a sorghum–corn–soybean–winter wheat rotation (sequence 2), and was also managed with synthetic fertilizer, herbicides and mechanical tillage. The OAM treatment included soybean–corn–soybean–winter wheat (sequence 1) or soybean–sorghum–soybean–winter wheat (sequence 2), and was typically managed with frequent mechanical tillage for weed control and bovine manure applications before the corn/sorghum or winter wheat phase of the rotation. Lastly, the OGM treatment included an alfalfa–alfalfa–corn–winter wheat rotation (sequence 1) or an alfalfa–alfalfa–sorghum–winter wheat rotation (sequence 2). Management of the OGM treatment included frequent mechanical tillage for weed control and limited bovine manure applications to alleviate potential phosphorus deficiency. Based on a 13-year average analysis of the bovine feedlot manure source utilized in the organic treatments, the total nitrogen content was 1.42% and the total phosphorus content was 0.72% (dry matter basis).

For analysis of the weed community, the two sequences within a management treatment were always pooled, because weed communities were similar between the corn and sorghum split-plots. The differences between split-plot

Table 2. Typical field operations and rates for corn in four long-term cropping systems at the UNL ARDC near Mead, Nebraska in 2007 and 2008. Numbers in parentheses indicate the years in which the particular application occurred. CR, conventional; DIR, diversified conventional; OAM, organic animal manure based; OGM, organic green manure based.

	Cropping system			
Field operation	**CR**	**DIR**	**OAM**	**OGM**
Spring disking[1]	x	x	x	x
Apply N fertilizer				
Ammonium nitrate 34-0-0	112 kg ha^{-1} (07)	112 kg ha^{-1} (07)		
Urea 46-0-0	116 kg ha^{-1} (08)	116 kg ha^{-1} (08)		
Apply bovine manure			45 tons ha^{-1} (07–08)	
Field cultivation[2]	x	x	x	x
Apply PRE herbicide[3]				
Metolachlor	2.3 litres ha^{-1} (08)	2.3 litres ha^{-1} (08)		
Atrazine 4L	3.5 litres ha^{-1} (08)	3.5 litres ha^{-1} (08)		
Acetochlor	8.2 litres ha^{-1} (07)	8.2 litres ha^{-1} (07)		
Planting[4]	57,300 seeds ha^{-1}	57,300 seeds ha^{-1}	57,300 seeds ha^{-1}	57,300 seeds ha^{-1}
Inter-row cultivation[5]	x	x	x	x
Rotary hoeing[6]			x	x
Hand weeding[7]	x	x	x	x
Harvest	x	x	x	x

[1] Spring disking occurred twice on April 20, 2007 and twice on May 13, 2008 in all treatments.
[2] Field cultivation occurred on May 14, 2007 in all treatments.
[3] PRE herbicides were applied to the CR and DIR treatments on May 17, 2007 and May 21, 2008.
[4] In 2007, corn was planted on May 14 in the CR and OAM treatments and on May 17 in the DIR and OGM treatments. In 2008, corn was planted on May 15 in all treatments.
[5] In 2007, inter-row cultivation occurred on June 7 and 21 in the OAM and OGM treatments and June 21 in the CR and DIR treatments. In 2008, inter-row cultivation occurred on June 19 in all treatments.
[6] In 2007, the OAM and OGM treatments were rotary hoed twice on May 17 and once more on May 21. In 2008, the OAM and OGM treatments were rotary hoed twice on June 3.
[7] In 2008, the OAM treatments were hand weeded on August 1, and all treatments were hand weeded on August 13 or 20.

sequences were considered for yield and economic analysis (data not shown).

For the OGM treatment, alfalfa was planted in rows spaced 0.25 m apart and typically occurred between early August and late September. Alfalfa was then cut and baled three times per season and destroyed with a moldboard plow at the end of the second year. For the DIR, OGM and OAM treatments, wheat also was planted in rows spaced 0.25 m apart. Wheat was typically planted between mid-October to mid-November. Soybeans in the DIR treatment were planted in rows spaced 0.25 m apart, but for all other treatments soybeans were planted in rows spaced 0.76 m apart to allow mechanical inter-row cultivation. The timing of soybean planting was typically mid-May to late-May for all treatments. Corn and sorghum were planted in rows spaced 0.76 m apart for all treatments. Corn was typically planted between late-April to mid-May, while sorghum was planted between mid-May to late-May. The timing of field operations for corn, sorghum, soybean and wheat within each treatment are summarized in Tables 2–5, respectively.

Weed community sampling

The above-ground weed sampling was coupled with weed seedbank analysis to quantify the differences among treatments in grass and broadleaf weed pressure and weed species diversity. Two methods were used to measure the weed seedbank: elutriation of soil seedbank samples and weed emergence from soil samples placed in greenhouse conditions. Weed seedbanks were sampled in late fall (post-harvest) following the 2007- and 2008-cropping seasons. Twelve 3.18-cm diameter cores were taken from each split-plot to a depth of 20 cm in 2007 (JMC Large Diameter Sampling Tube, JMC Soil Samplers, Newton, Iowa, USA). In 2008, cores were taken to a depth of 10 cm. Soil cores were taken from each split-plot in an 'X-pattern'[37]. In 2007, each core was split into two sections (0–10 cm and 10–20 cm depths) and the samples were pooled by split-plot and depth. The 0–10 cm depth represented the tillage layer (the maximum depth of tillage operations in the CR, DIR and OAM treatments) and the 10–20 cm depth represented the plow layer (the additional depth of tillage operations in the OGM treatment).

The samples were homogenized, dried, and a sub-sample weighing 200 g was elutriated and the remaining seeds were sorted and counted. To select a sub-sample, soil was passed through a sieve with 12.5 mm openings. Soil aggregates too large to pass through the screen were gently broken with a mortar and pestle. Soil was then poured through a funnel over a pie-chart grid. Soil particles and seeds fell randomly

Table 3. Typical field operations and rates for sorghum in four long-term cropping systems at the UNL ARDC near Mead, Nebraska in 2007 and 2008. Numbers in parentheses indicate years in which the particular application occurred. CR, conventional; DIR, diversified conventional; OAM, organic animal manure based; OGM, organic green manure based.

	Cropping system			
Field operation	**CR**	**DIR**	**OAM**	**OGM**
Spring disking[1]	x	x	x	x
Apply N fertilizer				
Ammonium nitrate 34-0-0	108 kg ha^{-1} (07)	108 kg ha^{-1} (07)		
Urea 46-0-0	116 kg ha^{-1} (08)	116 kg ha^{-1} (08)		
Apply bovine manure			45 tons ha^{-1} (07–08)	
Field cultivation[2]	x	x	x	x
Apply PRE herbicide[3]				
Atrazine 4L	2.9 litres ha^{-1} (07–08)	2.9 litres ha^{-1} (07–08)		
Metolachlor	2.3 litres ha^{-1} (07–08)	2.3 litres ha^{-1} (07–08)		
Planting[4]	321,000 seeds ha^{-1}	321,000 seeds ha^{-1}	321,000 seeds ha^{-1}	321,000 seeds ha^{-1}
Apply POST herbicide[5]				
Bentazon	2.3 litres ha^{-1} (08)	2.3 litres ha^{-1} (08)		
Atrazine 4L	2.3 litres ha^{-1} (08)	2.3 litres ha^{-1} (08)		
Inter-row cultivation[6]	x	x	x	x
Rotary hoeing[7]			x	x
Hand weeding[8]	x	x	x	x
Harvest	x	x	x	x

[1] Spring disking occurred twice on April 20, 2007 and twice on May 13, 2008 in all treatments.
[2] Field cultivation occurred on May 21, 2007 in all treatments.
[3] PRE herbicides were applied to the CR and DIR treatments on May 23, 2007 and May 21, 2008.
[4] Sorghum was planted on May 22, 2007 and May 20, 2008 in all treatments.
[5] POST herbicides were applied to the CR and DIR treatments on July 3, 2008.
[6] Inter-row cultivation occurred on June 20, 2007 and July 1, 2008 in all treatments.
[7] In 2007, the OAM and OGM treatments were rotary hoed on June 7 and 11. In 2008, the OAM and OGM treatments were rotary hoed on June 3 and 10.
[8] In 2007, the OAM and OGM treatments were hand weeded on July 24. In 2008, the OGM treatment was hand weeded on July 23, the OAM treatment was hand weeded on August 1, and all treatments were hand weeded on August 13 or 20.

onto the grid and a wedge-shaped area of the pie chart was selected; the width of the wedge increased until 200 g of soil were obtained. Seeds were separated from soil by water using an elutriator based on designs outlined by Wiles et al.[38]. One sub-sample was placed in a 100 mesh strainer screen measuring 6.0 cm in diameter, 17.5 cm in length, capped (Tube Cap No. 372, Niagara Plastics, Erie, Pennsylvania, USA) then washed in the elutriator for 2 h. The material remaining in the strainer screen was drained on a coffee filter, allowed to dry on a greenhouse bench then stored in a coin envelope. Envelope contents were later poured onto a plate marked with a grid upon which weed seeds were selected, identified and counted. Seeds of the *Amaranthus* genus were pooled with *Chenopodium album* seeds, due to the difficulty of identifying similar small-seeded weed species.

In 2008, an additional 800 g sub-sample of soil was spread in a 25.4 × 25.4 cm greenhouse flat to evaluate weed seedbank community diversity using the greenhouse emergence method[30]. The greenhouse temperature was maintained between 18 and 30°C and the samples were exposed to natural daylight hours from January–March. The samples were evenly spread over a 3 cm layer of sterile greenhouse potting soil and watered once every 48 h with a heavy mist. Seedlings were identified, counted and removed from the flats as they emerged. After 6 weeks of emergence, the samples were dried and exposed to an average outdoor temperature of −2°C for 1 week to break the seed dormancy of weed species. The samples were then placed back in the greenhouse and monitored for an additional 5 weeks before termination. The greenhouse emergence method measures the viable non-dormant weed seedbank, while the elutriation method measures the total weed seedbank.

The above-ground weed biomass (2007 and 2008) and broadleaf weed species diversity (2008) were sampled at physiological maturity of the crop in each treatment (early July in the wheat phase and mid-September in the corn, sorghum and soybean phases). These samples were not taken in the alfalfa phases of the OGM treatment. The above-ground weed biomass and weed species diversity were obtained by clipping all weeds at the soil surface in three randomly selected 1.16 m^2 quadrats (0.76 m × 1.52 m) per split-plot. Clipped plants were counted by weed species (2008), divided into grass and broadleaf weed species, then dried at 50°C to constant mass and weighed.

Table 4. Typical field operations and rates for soybean in three long-term cropping systems at the UNL ARDC near Mead, Nebraska in 2007 and 2008. Numbers in parentheses indicate years in which the particular application occurred. CR, conventional; DIR, diversified conventional; OAM, organic animal manure based.

	Cropping system		
Field operation	**CR**	**DIR**	**OAM**
Spring disking[1]	x	x	x
Field cultivation[2]	x	x	x
Apply PRE herbicide[3]			
Metolachlor	2.3 litres ha^{-1} (07)	2.3 litres ha^{-1} (07–08)	
Metribuzin + chlorimuron ethyl		0.51 litres ha^{-1} (08)	
Drill plant (0.25 m rows)[4]		642,000 seeds ha^{-1}	
Plant (0.76 m rows)[4]	59 kg ha^{-1}		59 kg ha^{-1}
Apply POST herbicide[5]			
Glyphosate		2.3 litres ha^{-1} (07–08)	
Bentazon	2.3 litres ha^{-1} (07–08)		
Metolachlor	2.3 litres ha^{-1} (08)		
Clethodim	0.59 litres ha^{-1} (07–08)		
Inter-row cultivation[6]	x		x
Rotary hoeing[7]	x		x
Hand weeding[8]	x		x
Harvest	x	x	x

[1] Spring disking occurred twice on April 20, 2007 and twice on May 13, 2008 in all treatments.
[2] In 2007, field cultivation occurred on May 21 in all treatments and once more on May 29 in the CR and OAM treatments. In 2008, field cultivation occurred twice on June 3 in the unplanted OAM plots and once in the CR treatment.
[3] In 2007, PRE herbicides were applied to the DIR treatment on May 17 and to the CR treatment on May 31. In 2008, PRE herbicides were applied to the DIR treatment on May 21.
[4] In 2007, soybeans were planted on May 21 in the DIR treatment, May 21 or May 29 in the OAM treatment and on May 29 in the CR treatment. In 2008, soybeans were planted on May 20 in the DIR treatment, May 20 (early) or June 4 (late) in the OAM treatment and on June 4 in the CR treatment.
[5] In 2007, POST herbicides were applied to the CR and DIR treatment on July 12 or 16. In 2008, POST herbicides were applied to the CR treatment on June 17, July 30 and August 4 and to the DIR treatment on July 3.
[6] In 2007, inter-row cultivation occurred on June 21 in the CR and OAM treatments and again on July 18 in the OAM treatment. In 2008, early soybeans in the OAM treatment were cultivated on June 30 and July 11 and the late soybeans in the OAM treatment were cultivated on July 2 and July 10. The CR treatment was cultivated on July 10 and 31.
[7] In 2007, the OAM treatment was rotary hoed on June 6, 7 and 11. In 2008, early soybeans in the OAM treatment were rotary hoed twice on June 3 and once on June 10. Late soybeans in the OAM treatment were rotary hoed once on June 10 and twice on June 23. The CR treatment was rotary hoed twice on June 23.
[8] In 2007, the OAM treatment was hand weeded on July 23. In 2008, late soybeans in the OAM treatment were hand weeded on July 22 and 29. All soybeans in the OAM treatment were hand weeded on August 4 or 12. The CR treatment was hand weeded on August 12.

Data analysis

The following equation was used to determine weed seedbank density; $D = (N * 1.16 * 10 * 10{,}000)/200$, where D is the weed seedbank density m^{-2} of a given soil depth, N is the number of individuals in a given sample, 1.16 is the average soil bulk density of the experimental site (g cm^{-3}), 10 is the depth of the soil sample (cm), 10,000 = cm^3 m^{-3} and 200 is the mass of each subsample (g).

Using the weed seedbank data and the above-ground weed species density, we calculated the indices of weed species diversity, evenness and richness for each split-plot. Diversity (H') was calculated using the Shannon diversity index; $H' = -\sum P_i(\text{Ln } P_i)$, where $P_i = N_i/N_{\text{total}}$, where N_i is the number of individuals of species i (plants m^{-2}) and N_{total} is the total number of individuals (plants m^{-2}). Evenness (J) was then calculated as $J = H'/\text{Ln } (S)$, where S is the species richness calculated as the total number of species per plot[39].

Estimates of H', J and S for the weed seedbank, along with weed seedbank density of grass and broadleaf weed species were then compared among management treatments using PROC MIXED (SAS Version 9.1, SAS Institute, Cary, North Carolina, USA). Fixed effects in the model included current crop, management treatment (e.g., OAM), crop sequence, year, block and year × management treatment (to determine if the data could be pooled across years). Crop sequence and the current crop were then pooled by common management treatment (e.g., OAM sequence 1 and OAM sequence 2 for all current crops combined into OAM) for comparison among management treatments using orthogonal contrasts. Current crop and rotation sequences were pooled by management treatment in the model for weed seedbank analyses, because many

Table 5. Typical field operations and rates for wheat in three long-term cropping systems at the UNL ARDC near Mead, Nebraska in 2006–2007 and 2007–2008 seasons. DIR, diversified conventional; OAM, organic animal manure based; OGM, organic green manure based.

	Cropping system		
Field operation	**DIR**	**OAM**	**OGM**
Pre-plant disking[1]	x	x	x
Apply N fertilizer			
Ammonium nitrate 34-0-0	68 kg ha^{-1}		
Planting[2]	134 kg ha^{-1}	134 kg ha^{-1}	134 kg ha^{-1}
Harvest for grain	x	x	x
Apply herbicide to stubble[3]			
Glyphosate	2.3 litres ha^{-1}		
Disk stubble[4]	x	x	x
Field cultivate stubble[5]		x	x
Chisel plow stubble[6]		x	x
Mow stubble[7]	x		

[1] In 2006, pre-plant disking occurred on October 17 and 23 in all treatments. In 2007, pre-plant disking occurred on October 4 in the OAM treatment and on November 1 in the OGM treatment.
[2] In 2006, winter wheat was planted on October 23 in the OGM treatment and on October 25 in the DIR and OAM treatments. In 2007, wheat was planted on October 4 in the DIR and OAM treatments and on November 1 in the OGM treatment.
[3] Herbicide was applied to wheat stubble in the DIR treatment on July 12, 2007.
[4] In 2006, wheat stubble was disked once on July 24 and twice more on August 31 in the OAM and OGM treatments. The DIR treatment was disked once on August 31. In 2007, wheat stubble was disked on July 17 and August 1 in the OAM and OGM treatments and once more on September 6 in the OAM treatment. The DIR wheat stubble was disked twice on September 6.
[5] Wheat stubble was field cultivated once in the OAM treatment and twice in the OGM treatment on September 7, 2006 and August 15, 2007.
[6] Wheat stubble was chisel plowed on July 24, 2006 in the OAM and OGM treatments.
[7] Wheat stubble was mowed on August 29, 2006 in the DIR treatment.

weed seeds persist in the soil for more than a year[18,19]. Thus, the long-term management and crop rotation were more likely to explain the variability of the weed seedbank. The tillage layer (2007 and 2008) and the plow layer (2007) were both analyzed for differences in weed seedbank density among management treatments, but for weed seedbank diversity only the tillage layer was analyzed, as seeds in this layer were more likely to emerge.

PROC MIXED also was used to analyze the aboveground grass and broadleaf weed biomass within each crop (excluding alfalfa) of the four management treatments. The standing weed community is often influenced by current crop and management system[40]; thus, the current crop and management treatment were both included in the model along with year, block and year × management treatment. Rotation sequences were pooled by common management treatment within crops (e.g., OAM sequence 1 pooled with OAM sequence 2) for comparison among management treatments using orthogonal contrasts. A significance level of $\alpha = 0.05$ was chosen to indicate the statistical difference in all analyses.

Results and Discussion

Weed species diversity

The Shannon index for diversity (H') of the weed seedbank ranged from 0.37 to 1.12, depending on the management treatment and year (Fig. 1a, d), when using the weed seedbank elutriation method. Weed seedbank diversity was generally greater in 2008 than 2007, and greatest in the OGM treatment in both years. In 2007, the diversity did not differ between the CR and OAM treatments or between the DIR and OAM treatments, but the diversity was greater in the DIR treatment compared to the CR treatment. In 2008, the diversity in the OGM treatment was greater than the diversity in the OAM and DIR treatments, but not the CR treatment ($P = 0.064$). The diversity did not differ between the CR, DIR or OAM treatments. When the organic treatments (OAM and OGM) were contrasted with the conventional treatments (CR and DIR), the diversity was greater in the organic treatments in 2007 and 2008.

The evenness (J) of weed species within the seedbank ranged from 0.31 to 0.61, depending on the management treatment and year (Fig. 1b, e). As with diversity, the evenness was generally greater in 2008 than 2007 and greatest in the OGM treatment in 2007. Evenness was not different between the CR and DIR treatments or between the CR and OAM treatments, but was greater in the DIR treatment compared to the OAM treatment in 2007. In 2008, the evenness of the weed seedbank was not different among the OGM, OAM and CR treatments, but was greater in the OGM treatment compared to the DIR treatment.

Richness (S) within the weed seedbank ranged from 2 to 6 weed species, depending on the management treatment and year (Fig. 1c, f). In 2007, the weed seedbank

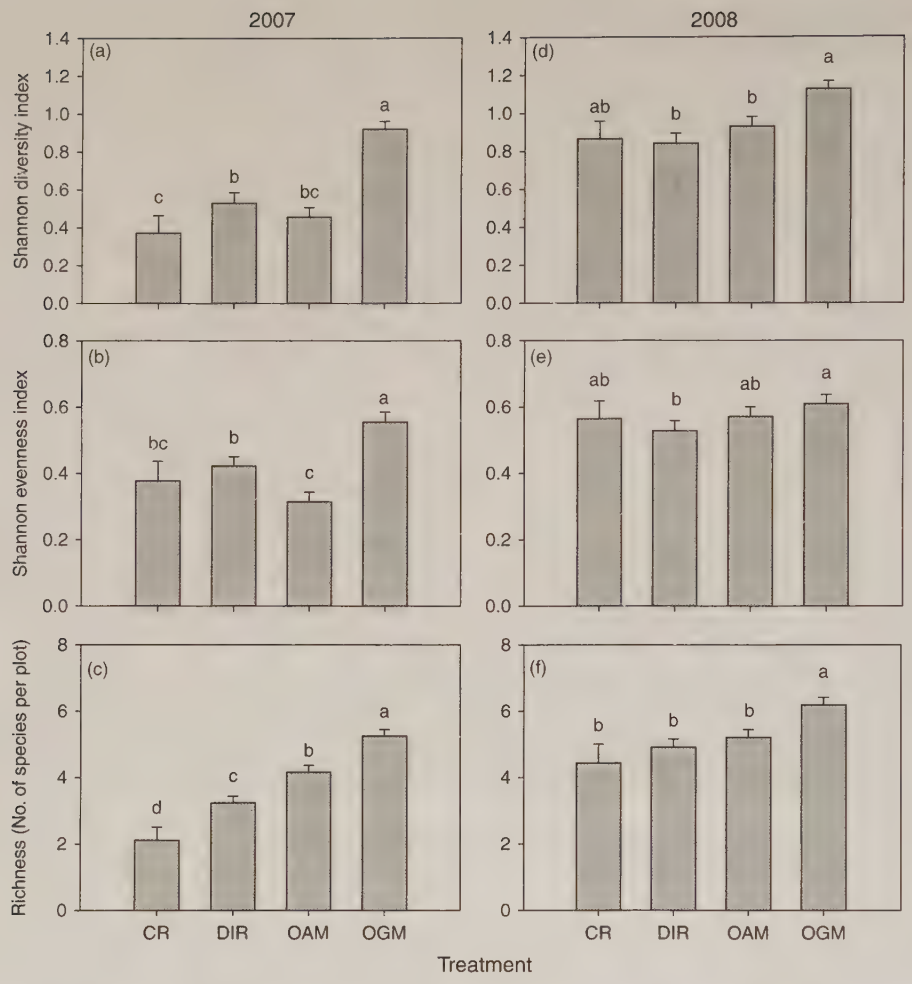

Figure 1. Weed seedbank (a, d) diversity, (b, e) evenness and (c, f) richness in 2007 (a–c) and 2008 (d–f) based on the Shannon diversity index from the 0 to 10 cm soil depth in CR, DIR, OAM and OGM treatments. Data collected using the seedbank elutriation method. Bars represent the standard error of the mean. Letters above the bars represent differences between treatments ($P < 0.05$).

richness was greatest in the OGM treatment, followed by the OAM treatment, the DIR treatment and the CR treatment. In 2008, the weed seedbank richness was again greatest in the OGM treatment, but was not different among the remaining treatments. Weed species richness in the seedbank was greater in 2008 than 2007.

The greenhouse emergence method was only utilized in 2008 and resulted in greater estimates of the weed species diversity relative to the seedbank elutriation method (1.07–1.38 compared to 0.84–1.12), because the seedbank elutriation method may exclude small-seeded weed species, due to the size of sieves used in the elutriation process. The sample size used in the greenhouse method was also larger (800 g of soil compared to 200 g elutriated). Thus, the probability of collecting a low-density weed species is greater in the greenhouse emergence method. Moreover, the *Amaranthus* spp. were not pooled with the *C. album* individuals in the greenhouse emergence method as they were in the elutriation method. Despite the benefits of the greenhouse emergence method, the elutriation method is necessary to account for dormant seeds.

Weed seedbank diversity (H') was greatest in the OAM and OGM treatments in 2008. The diversity did not differ between the CR and DIR treatments (Fig. 2a). Weed seedbank evenness (J) did not differ among any treatments (Fig. 2b), whereas weed seedbank richness (S) was greatest in the OGM treatment, followed by the OAM treatment, and richness did not differ between the conventional treatments (Fig. 2c).

The above-ground broadleaf weed diversity was only measured in 2008 and was lower than the weed seedbank species diversity, ranging from 0.34 to 0.78. The above-ground broadleaf weed diversity (H') was greatest in the OGM treatment in 2008, but the diversity did not differ among the remaining treatments (Fig. 3a). Weed species evenness (J) did not differ between the OGM and CR treatments, but evenness was greater in the OGM treatment compared to the DIR and OAM treatments (Fig. 3b). Weed species richness (S) of the OGM treatment was greater than the CR and DIR treatments, but not the OAM treatment. Richness of the OAM treatment was greater than the CR treatment, but not the DIR treatment. There was no

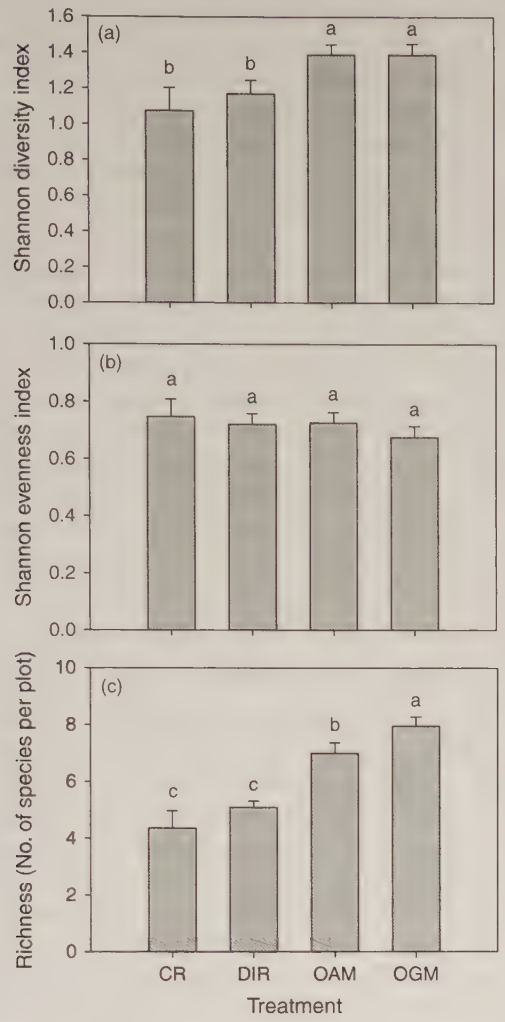

Figure 2. Weed seedbank (a) diversity, (b) evenness and (c) richness based on the Shannon diversity index from the 0 to 10 cm soil depth in CR, DIR, OAM and OGM treatments in 2008. Data collected using the greenhouse emergence method. Bars represent the standard error of the mean. Letters above the bars represent differences between treatments ($P < 0.05$).

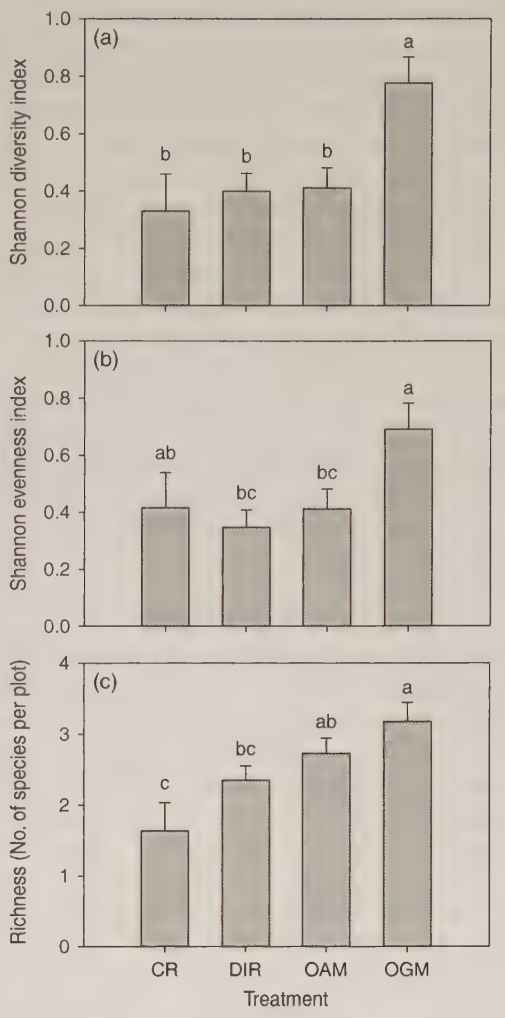

Figure 3. Above-ground broadleaf weed species (a) diversity, (b) evenness and (c) richness based on the Shannon diversity index in CR, DIR, OAM and OGM treatments in 2008. Bars represent the standard error of the mean. Letters above the bars represent differences between treatments ($P < 0.05$).

difference in the weed species richness between the conventional treatments (Fig. 3c).

Across all sampling methods, weed species diversity was generally greatest in the OGM treatment. Weed seedbank diversity was greatest in the OGM treatment in 2007 using the elutriation method and in 2008 when measuring the above-ground broadleaf diversity. The OGM treatment shared the greatest diversity with the CR treatment using the seedbank elutriation method and the OAM treatment using the greenhouse emergence method in 2008. The greater diversity observed in the OGM treatment may be the result of several factors. Similar to the DIR treatment, the crop rotation in the OGM treatment contains a diverse selection of crop species. While the DIR treatment contains the most crop species (four), the OGM treatment contains one summer annual, one winter annual and one perennial crop, resulting in the greatest phenological diversity. However, there appeared to be other factors driving weed diversity across treatments.

Due to the greater level of crop richness and diversity of crop phenology present in the DIR treatment compared with the CR treatment, we expected greater levels of weed diversity (H') in the DIR treatment[10,26]. We observed this in 2007; weed seedbank diversity using the elutriation method was greater in the DIR treatment compared to the CR treatment. The diversity did not differ between the two conventional treatments using any method in 2008. While weed diversity was greater in the DIR treatment in 2007, the inconsistent relationship between crop diversity and weed diversity across years suggests that the use of herbicide inhibits any weed diversity that may have been favored by increased crop diversity. An increasing diversity of crop species has been shown to promote a greater diversity of weed species[10], but there appear to be other factors contributing to the varying levels of diversity in this study.

The diversity of management practices in a cropping system may contribute to the diversity of the weed community. During the corn, sorghum and wheat phases of the OGM treatment, management was similar to management of the OAM treatment, consisting of mechanical field cultivations and rotary hoeing during the corn or sorghum phase and no mechanical weed control during the wheat phase. The inclusion of perennial forage in the OGM treatment required an entirely different management scheme. For 2 years of the 4-year cycle, mechanical cultivation and rotary hoeing were no longer required and weeds were managed as a result of the hay cuttings that occurred three or four times through the growing season. Furthermore, at the conclusion of the 2-year alfalfa stage, the treatment was moldboard plowed to destroy the forage crop. These two additional management measures increased the diversity of management within the OGM treatment, which may have contributed to the increased levels of weed species diversity.

Cutting alfalfa three or four times per growing season shifted the competitive advantage to grass weed species in the OGM treatment. The grass weed species can withstand multiple cuttings (unlike many broadleaf weed species) and the lower crop canopy following a cutting allows light to reach many grass weed species[28–30]. Furthermore, it is unlikely that many dominant summer annual broadleaf weed species (e.g., pigweed) were able to produce seed due to the multiple cuttings. The competitive advantage of a group of weed species is unlikely to shift in the OAM, DIR and CR treatments, because the weed management tactics are relatively static within a given treatment throughout the 4-year cycle (with the exception of wheat and soybeans planted to 0.25 m rows, which eliminated mechanical cultivation as a management option). This was evident while observing the population density of *Amaranthus/Chenopodium* spp. in the OAM treatment. The density of these two broadleaf weed species in the OAM weed seedbank greatly exceeded that of all other treatments (data not shown), likely due to a lack of diverse crop phenology and management practices in the rotation, which allows competitive weed species to dominate the weed community. The increased density of *Amaranthus/Chenopodium* spp. was also due to the dense population of these seeds found in the animal manure source (data not shown). Seeds of both weed species are very small with a hard seed coat, allowing many seeds to remain viable even after passing through the animal's digestive system[41]. The introduction of these weed species through the application of bovine manure in the OAM treatment lowered the species evenness of the weed community and thus the overall weed species diversity.

Previous studies have shown that weed species evenness (*J*) is greater in monoculture systems coupled with the intensive use of herbicides compared to diverse rotations coupled with low inputs[23–25]. These results were not observed in our study, as there was no consistent difference among treatments, and when there was a difference, the OGM treatment exhibited the greatest levels of weed species evenness. As previously discussed, the diversity of management schemes required when perennial forage was included in the rotation likely reduced the dominance of many summer annual broadleaf weed species in the weed community. The management of those dominant broadleaf weed species led to greater levels of evenness, thus greater weed species diversity.

Weed seedbank richness (*S*) was also greatest in the OGM treatment, followed by the OAM and conventional treatments. These results are consistent with previous studies, in that the use of herbicides may eliminate small populations of susceptible weed species[42] resulting in relatively greater weed species richness in low-input cropping systems[25]. The greater level of weed species richness in the OGM treatment relative to the OAM treatment may be due to the niche that perennial forage in the rotation provides to weed species adapted to multiple cuttings[28–30].

Weed seedbank composition

In 2007, the density of broadleaf weed species in the tillage layer of the CR, DIR, OAM and OGM treatments was dominated by *Amaranthus/Chenopodium* spp. seeds (87, 93, 93 and 86%, respectively). The broadleaf weed seedbank density was greatest in the OAM treatment (89,073 seeds m^{-2}), followed by the OGM treatment (57,381 seeds m^{-2}) and was not different within the DIR (22,336 seeds m^{-2}) and CR (14,658 seeds m^{-2}) treatments. The *Amaranthus/Chenopodium* spp. seeds also dominated the broadleaf weed seedbank in the plow layer of the CR, DIR, OAM and OGM treatments (92, 97, 94 and 89%, respectively). However, in the plow layer the broadleaf weed seedbank density was greatest in the OGM treatment (52,512 seeds m^{-2}) followed by the OAM treatment (24,675 seeds m^{-2}) and was not different within the DIR (17,395 seeds m^{-2}) and CR (9902 seeds m^{-2}) treatments.

Dominant grass weed species in the tillage layer included *Setaria* and *Digitaria* spp. The grass weed species seedbank density in the tillage layer was greatest in the OGM treatment (26,978 seeds m^{-2}), while grass weed species seedbank densities did not differ among the OAM (4769 seeds m^{-2}), CR (2799 seeds m^{-2}) and DIR (2224 seeds m^{-2}) treatments in 2007. Similar to the tillage layer, grass weed species seedbank densities in the plow layer were greatest in the OGM treatment (15,817 seeds m^{-2}) and did not differ among the OAM (1753 seeds m^{-2}), DIR (745 seeds m^{-2}) and CR (263 seeds m^{-2}) treatments.

Weed seedbank density was only measured in the tillage layer (0–10 cm) in 2008. Similar to 2007, *Amaranthus/Chenopodium* spp. dominated the broadleaf weed species community in the tillage layer of the weed seedbank in the CR, DIR, OAM and OGM treatments (86, 87, 85 and 73%, respectively). The broadleaf weed species seedbank density was greatest in the OAM (41,415 seeds m^{-2}) and OGM (37,567 seeds m^{-2}) treatments and did not differ between

the DIR (19,281 seeds m^{-2}) and CR (12,007 seeds m^{-2}) treatments. Also similar to 2007, the grass weed species seedbank community was dominated by *Setaria* and *Digitaria* spp. Grass weed species seedbank density was greatest in the OAM treatment (14,345 seeds m^{-2}), followed by the OGM treatment (10,699 seeds m^{-2}) and did not differ between the DIR (3941 seeds m^{-2}) and CR (3094 seeds m^{-2}) treatments. Total weed seedbank density was greater in 2007 than in 2008. Determining weed seedbank density using the elutriation method is useful for viable dormant seeds, but total densities may be inflated due to the inclusion of some non-viable weed seeds.

Overall, the broadleaf weed species seedbank density in the tillage layer was greatest in the OAM treatment and lowest in the two conventional treatments in both years. The density of the broadleaf weed species in the OAM treatment was greater than that of the OGM treatment in 2007. The greater density observed in the OAM treatment relative to the OGM treatment was expected. Several studies have shown that the inclusion of a perennial forage crop in a rotation can reduce broadleaf weed populations in low-input or organic systems[28,43–45]. Perennial forage crops in rotation can suppress weeds through competition[46], mowing[47], light extinction, changes in the soil thermal regime[48] and reduced levels of weed seed germination due to the lack of tillage[49]. Each of these factors may have contributed to the reduction of the broadleaf weed species seedbank density in the OGM treatment relative to the OAM treatment.

Another possible contribution to the density of the broadleaf weed species seeds in the tillage layer of the OAM treatment was the application of non-composted bovine manure every other year. Once in the seedbank, these broadleaf weed species may experience a competitive advantage in the nutrient-rich environment created in the OAM treatment. Compost applications have been shown to enhance the growth and competitive ability of common waterhemp[32]. *Amaranthus/Chenopodium* spp. are able to compensate for their initial size disadvantage through rapid growth and nutrient uptake, because the plant relative growth rate is negatively correlated with seed size[50] and nutrient enrichment consistently selects for fast-growing species that outcompete slower-growing, stress tolerant species[51–53]. Despite the increase in broadleaf seedbank density, animal manure application in the OAM treatment consistently increased the yields of corn, sorghum and winter wheat relative to the OGM treatment[54].

Weed seedbank density and distribution are mainly influenced by tillage system and weed management[21]. In this experiment, in 2007, the broadleaf weed species seedbank abundance in the plow layer (10–20 cm depth) was greatest in the OGM treatment, followed by the OAM treatment. This difference was likely due to the moldboard plow utilized to terminate the alfalfa stand every fourth year in the OGM treatment. The broadleaf weed species' seeds that may have accumulated in the tillage layer were likely inverted into the plow layer[55].

In 2007, the grass weed seedbank density of the tillage and plow layer was greatest in the OGM treatment, which was expected due to the competitive advantage gained by the grass weed species in the perennial forage phase of the rotation[28–30]. However, in 2008, the density of grass weed species was greatest in the OAM treatment. The lack of herbicide management and timely cultivations in 2008, along with the nutrient-rich soil environment may have contributed to the greater grass density in the OAM treatment[8,51–53]. The spring months of 2008 were unusually wet, which restricted timely cultivation in the organic rotations. As a result, grass weed species populations (e.g., *Setaria* spp.) became troublesome in OAM soybeans. Reduced organic weed control in unusually wet years has been demonstrated in previous studies[45,56]. Our results suggest that weed community shifts are driven by a combination of environmental and management factors.

Above-ground weed biomass

The broadleaf weed biomass was greater in the OAM corn treatment (923 kg ha^{-1}) than in the CR and DIR corn treatments (42 and 254 kg ha^{-1}, respectively) in 2007 and 2008 (Fig. 4). The broadleaf weed biomass in the OGM corn treatment (613 kg ha^{-1}) was not different from any other treatment. However, when the organic treatments were contrasted with the conventional treatments, the broadleaf weed biomass was greater in the organic treatments. In soybean, the broadleaf weed biomass in the OAM treatment (309 kg ha^{-1}) was greater than the biomass in the CR and DIR treatments (59 and 15 kg ha^{-1}, respectively). There were no differences in the broadleaf weed biomass among any treatments in sorghum or wheat (Fig. 4). The broadleaf weed biomass in sorghum for the CR, DIR, OAM and OGM treatments was 175, 123, 225, and 250 kg ha^{-1}, respectively. Similarly, the broadleaf weed biomass in wheat for the DIR, OAM and OGM treatments was 188, 108, and 167 kg ha^{-1}, respectively. These results may suggest that sorghum and wheat are more competitive with summer annual broadleaf weeds, making these crops more competitive options in organic cropping systems with greater weed pressure. The phenology (winter annual), dense plant spacing and tillering capacity of wheat may prevent the germination and growth of many dominant summer annual weeds. Both sorghum and wheat have demonstrated allelopathic effects on weeds, but one would expect this to impact weed populations in the subsequent crop[57,58]. There were no differences in the broadleaf weed biomass within the organic rotations. This was somewhat unexpected, due to the high broadleaf weed seedbank density observed in the OAM treatment across both years. While including perennial forage in the rotation may aid in the reduction of the broadleaf weed seedbank, in this study, the above-ground weed biomass was unaffected.

The grass weed biomass in corn was greatest in the OGM treatment (3102 kg ha^{-1}; Fig. 5). The grass weed biomass in the OAM treatment (1565 kg ha^{-1}) was greater than the

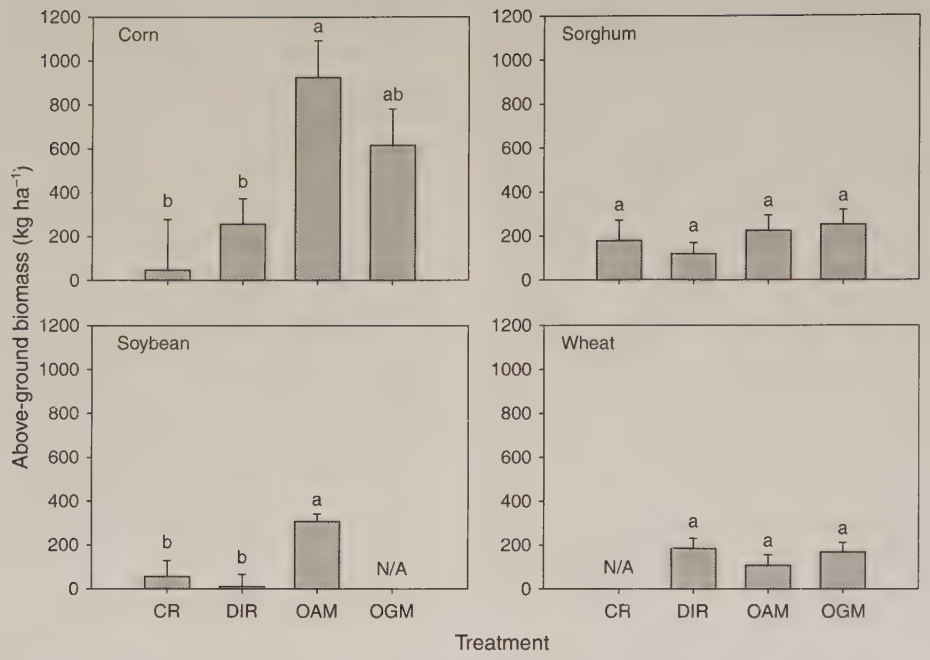

Figure 4. Above-ground dry broadleaf weed biomass in corn, sorghum, soybean and wheat among CR, DIR, OAM and OGM treatments for both 2007 and 2008. Bars represent the standard error of the mean. Different letters above the bars represent differences between treatments ($P < 0.05$). An 'N/A' above a treatment indicates that the crop is not included in the treatment.

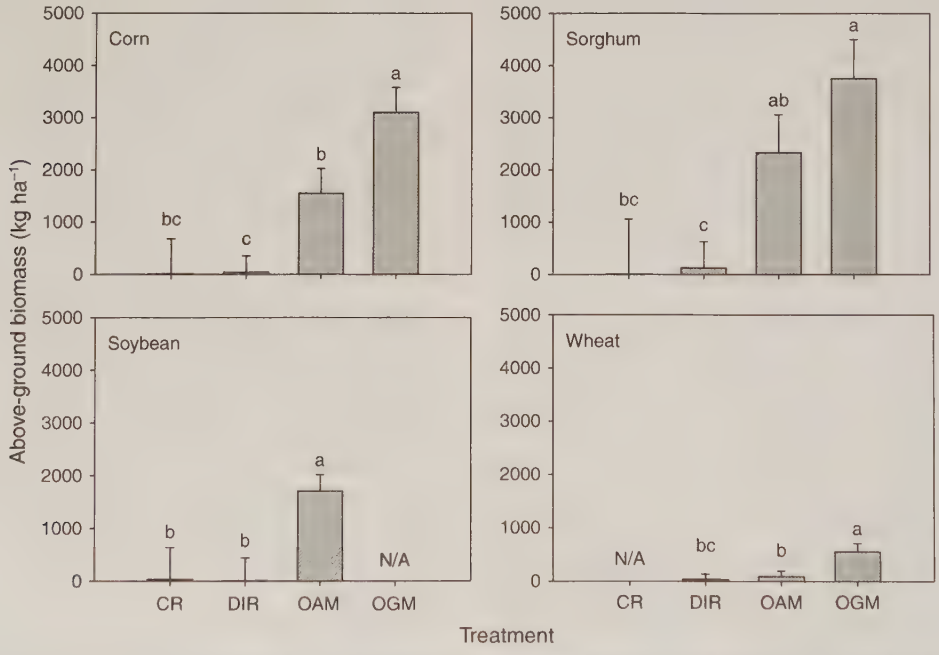

Figure 5. Above-ground dry grass weed biomass in corn, sorghum, soybean and wheat among CR, DIR, OAM and OGM treatments for both 2007 and 2008. Bars represent the standard error of the mean. Different letters above the bars represent differences between treatments ($P < 0.05$). An 'N/A' above a treatment indicates that the crop is not included in the treatment.

biomass in the DIR treatment (37 kg ha^{-1}) but not the CR treatment (22 kg ha^{-1}). In sorghum, the grass biomass was greatest in the OGM treatment (3737 kg ha^{-1}) followed by the OAM, DIR and CR treatments (2335, 110 and 13 kg ha^{-1}, respectively). In soybean, the grass weed biomass was greatest in the OAM treatment (1715 kg ha^{-1}) and did not differ between the CR and DIR treatments (34 and 0 kg ha^{-1}, respectively). In wheat, the grass weed biomass was greatest in the OGM treatment (562 kg ha^{-1}) and did not differ between the DIR and OAM treatments (28 and 84 kg ha^{-1}, respectively; Fig. 5). These results were expected due to the lack of herbicide management in the

organic treatments and the greater grass weed seed production during the alfalfa stage of the OGM rotation[28–30]. Given the high grass weed seedbank density observed in the OGM treatment combined with a lack of timely mechanical weed control, due to early season rain events, the exceptionally high grass weed biomass in the OGM treatment was not unexpected. These results emphasize the importance of minimizing the seedbank density to reduce the above-ground weed biomass in subsequent years.

Conclusions

The results of this study demonstrate that the inclusion of perennial forage such as alfalfa in organic cropping systems may contribute to the increase of weed biodiversity. Moreover, organic cropping systems that rely heavily on animal manure applications for soil fertility will decrease weed biodiversity. The potential for the addition of weed seed and the nutrient-rich environment created by the frequent bovine manure applications may shift the competitive advantage in the agroecosystem to a few dominant summer annual weeds. This dominance was evident in the abundant weed seedbank populations of broadleaf weeds such as *Amaranthus/Chenopodium* spp. in the OAM treatment. It is important to manage the abundant weed seedbank populations of grass weed species that may accumulate during the perennial forage stage of the rotation by improving the timing of alfalfa cuttings and increasing the population density and uniformity of the alfalfa stand to prevent grass weed seed shatter. The density of the weed seedbank influences the effectiveness of weed control, especially in organic systems, so it is important to prevent the accumulation of the weed seedbank[59,60].

Organic weed management is heavily reliant on mechanical cultivation, which is often limited by the weather in a given growing season. If the weather conditions permit the timely use of mechanical cultivation, the above-ground weed biomass can be managed at acceptable economic thresholds and organic crop yields are often comparable to conventional crop yields[45,56]. The high weed seedbank populations observed in this study also demonstrate the importance of timely weed management in organic crop rotations. Special attention should be given to additional management tactics for reducing weed seedbank density so as to increase the effectiveness of timely mechanical cultivations in organic cropping systems. An ecological approach consisting of multiple physical, biological and cultural tactics is likely the most effective method for reducing weed seedbank density on organic farms[61]. This approach employs a diverse range of weed management tactics (e.g., crop rotation, cover cropping, inter-cropping, soil amendments, rotary hoeing, flaming, etc.) that individually are weak, but together are strong[62]. This ecological approach to weed management was described by Liebman and Gallandt[63] as the 'many little hammers' approach where the cumulative effect of many 'little hammers' will approach the effectiveness of a 'big hammer' (e.g., synthetic herbicides)[63]. Moreover, an ecological approach to weed management may select for a more diverse weed community (of those weeds that remain). In this study, increasing the diversity of management operations in the OGM rotation seemed to contribute to greater levels of weed diversity.

While the OGM rotation increased crop and weed diversity and minimized broadleaf weed populations compared to the OAM rotation, grain yield loss was incurred primarily due to deficiencies in soil fertility[54]. Between 1996 and 2007, all grain yield differences among the conventional treatments (CR and DIR combined) and the OAM and OGM treatments were significant ($\alpha = 0.05$). Relative to the conventional treatments, the yield in the OAM and OGM treatments was reduced by 13 and 33% in corn, 16 and 27% in sorghum, respectively, and in wheat OAM yield increased by 9% while OGM yield was reduced by 15%[54]. Thus, a combination of management practices from the OAM and OGM treatments may be most appropriate for maximizing the yield and biodiversity, while minimizing weed density and the above-ground biomass.

The conservation of biodiversity is often seen as a moral, aesthetic, social or economic issue, but there is increasing evidence that the biodiversity of weed communities in agroecosystems provides several valuable ecological functions[64]. Maintenance of a diverse weed community is one step toward optimizing the sustainability of agroecosystems[65] through improved nutrient cycling and pest control[2], improved soil chemical and physical properties[1] and the reduction of soil erosion[3]. Furthermore, managing weed species diversity will promote the overall diversity of other trophic levels in the agroecosystem, including insects, birds and larger animals[64,66]. These potential benefits were not directly measured in this study, nor can we determine the level of plant diversity necessary to achieve these benefits. While the increases in weed diversity and weed species richness observed in this study are modest, they are significant. Further studies should be conducted to determine whether the gains in weed species diversity observed in organic cropping systems are sufficient to realize ecosystem services.

Previously, the task of preserving biodiversity had been left to unmanaged natural ecosystems, but unmanaged ecosystems are disappearing from the landscape[64]. As this happens, agroecosystems may emerge as a practical alternative ecosystem for the conservation of biodiversity[67]. Future studies in agroecosystem diversity should be directed toward developing organic cropping systems that maximize diversity while minimizing weed seedbank density and the above-ground biomass.

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Economic analysis of experimental organic agricultural systems on a highly eroded soil of the Georgia Piedmont, USA

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Abstract

Information about the costs and labor requirements of experimental organic farming systems designed to restore highly degraded soils in the southeastern US are needed. Enterprise budgets were prepared for the production of okra, hot pepper and a corn/winter squash intercrop under 10 different production systems, nine of which were based on organic conservation tillage. A stochastic dominance analysis was conducted to determine the relative risk efficiency of the 10 systems over the course of the experiment in terms of productivity, profitability and carbon sequestration potential. Organic conservation tillage treatments had lower tractor labor and fuel costs than conventional treatments, due to the extensive tillage required in conventional vegetable farming. The subset of organic treatments receiving compost addition without additional mulches also demonstrated increases in soil carbon, an important driver of system productivity. Organic treatments had little pest and pathogen pressure, with the exception of *Fusarium* wilt in some treatments receiving straw mulch. Weed suppression by straw mulches reduced labor requirements by an average of 23%. Yields in all treatments were lower than conventional yields from other studies in the region, due to the degraded nature of the soil on the study site. However, net returns on high-labor, organic crops were over US$30,000 ha^{-1} in some treatments. The results of this work indicate that organic, conservation tillage systems can restore soil productivity and command high returns per hectare if labor requirements can be met.

Key words: organic agriculture, alley cropping, conservation tillage, enterprise budget, stochastic dominance, soilcarbon, okra, peppers, winter squash

Introduction

Organic retail food sales have consistently grown approximately 20% annually since 1990[1], although certified organic cropland still only accounted for only 0.5% of agricultural lands in the US in 2005[2]. Fresh produce is the top-selling category in organic food production, and accounted for 42% of all organic food sales in 2001, with sales increasing 51.4% from 1999 to 2000[1]. In 2005, Georgia had 439,660 ha in vegetable production[3], and ranks in the top four states nationally for fresh market vegetables in area harvested, production and value[4]. Additionally, the southern and western regions of the US have been identified as the two fastest-growing organic markets in the country[5]. Despite the market potential for organic production in the state, in 2005, Georgia ranked 31st in the country in the number of certified operations and 43rd in the total number of certified organic acres, with only 53 certified organic operations in the state, totaling 2413 ha[2].

Economic decision-making tools may help alleviate the risk associated with converting to new production practices; enterprise budgets are one such tool. Enterprise budgets estimate the costs and returns associated with the production of a commodity, or enterprise[6]. While common for conventionally produced commodities, few enterprise budgets exist for organic agriculture, and even fewer for the Southeast. There are enterprise budgets for organic commodity crops in the Midwest, and for vegetables in California, Wisconsin and New Jersey[7]. Some production cost information for large-scale organic vegetable production has

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been assembled for the southeastern US[8], and is applicable to the large-scale farms in the southern coastal plains. Only one production cost study was found for the region that would be applicable to the small, diversified organic farms of northern Georgia Piedmont[9].

Although enterprise budgets allow the comparison of input costs and returns between systems, they do not account for changes in the environmental quality associated with production systems. Centuries of tillage-intensive agriculture have left the soils of Georgia Piedmont severely eroded, lacking topsoil, soil organic matter and any appreciable nutrients[10]. In order to restore sustained production to degraded soils, farmers must also restore soil quality, specifically the soil organic matter[11]. These challenges are intensified by the region's subtropical climate, which contributes to rapid pest and disease outbreaks, high weed pressure and rapid decomposition of soil amendments.

The purpose of this work was to provide an economic analysis of a field experiment that examined the ability of two experimental ecological agricultural systems to restore degraded soils in the southeastern US[12]. A 3-year field study was conducted to assess the effects of organic farming systems on soil characteristics, crop production and weed biomass. The two experimental systems were based on best management practices and recommendations from previous agroecological research in the region, including conservation tillage, incorporation of perennial legumes, crop rotation and use of winter cover crops and composts. This analysis was intended to assess the economic costs and benefits of the experimental systems on degraded soils using an enterprise budget approach and to discuss the results from a variety of crops in the rotation using a stochastic dominance analysis. Production economics for these experimental techniques is not intended to be representative of organic conservation tillage systems on fertile soils, but rather to contribute to the discussion of the potential profitability of experimental technologies on degraded lands. Enterprise budgets are presented here to contribute to basic production economics information that is lacking for the region as an aid in the grower's decision-making. Stochastic dominance analysis is employed to compare the risk-return trade-offs of the 10 production systems from crop productivity, economic profitability, to identify risk-efficient systems and discuss these results in the light of desired changes in parameters related to soil quality (soil carbon).

Production practices and methods

The study site was located on the Spring Valley Ecofarm, near Athens, Georgia, USA (33°57′N latitude, 83°19′W longitude). This historic farm had been in cultivation since 1864, with cotton, cattle, sorghum and soybean previously grown on the site until 1993. At this time, the site was removed from extensive cultivation and management shifted to a mowed fallow of pasture grasses and weeds. An alley cropping (AC) system utilizing perennial legumes was established on the site in 2001. AC is a technique where hedgerows of trees or shrubs are planted between rows, or alleys, of crop plants[13]. This technique is often practiced in the tropics where leguminous hedgerow species are used as a perennial source of crop fertility, animal fodder and erosion control[14–16]. In these systems, shoots of hedgerow plants are coppiced, and the pruned branches applied as a mulch and green manure for adjacent crop plants.

In 2004, an experiment was initiated that compared three cropping systems over a 3-year vegetable crop rotation for their effects on soil characteristics, plant production and yields[12]. These systems included two organic systems in conservation tillage, and one tillage-intensive conventional system, outlined further below. The subheadings below the cropping systems describe experimental treatments which employed three levels of compost for nutrient supply (0, 22.4 and 44.8 $Mg\,ha^{-1}\,yr^{-1}$), as well as two levels of mulch (with or without), for weed suppression. For a complete description of the experimental design and rationale, see Jacobsen and Jordan[12].

The three cropping systems and their treatments are as follows:

1. AC with organic vegetables using strip tillage (AC treatments) are as follows:
   (a) AC1: AC (including hedgerow prunings) with winter cover crops.
   (b) AC2: AC1 + straw mulch.
   (c) AC3: AC1 + spring compost.
   (d) AC4: AC1 + spring compost + mulch.
   (e) AC5: AC1 + fall compost + spring compost.
   (f) AC6: AC1 + fall compost + spring compost + mulch.
2. Organic vegetables using strip tillage [no AC, organic strip tillage (OST) treatments] are as follows:
   (a) OST1: winter cover crops + mulch.
   (b) OST2: OST1 + spring compost.
   (c) OST3: OST1 + fall compost + spring compost.
3. Conventionally fertilized, conventionally tilled vegetables [conventional tillage (CT) treatment].

A general outline of the annual management practices for each treatment is detailed in Table 1. In AC treatments, leguminous perennial hedgerows consisted of *Albizia julibrissin* planted in hedgerows 5 m apart with plants 0.5 m apart within the hedgerow. Hedgerows were coppiced using a hedge trimmer 1 to 3 times per summer when the leaves began to shade the adjacent crop plants. These prunings were applied by hand to adjacent cropped areas as a green manure in all AC treatments. Winter cover crops and crop plants were terminated using a commercial grass roller, or roller crimper, in the AC and OST treatments. This implement was used to flatten and kill cover crops before seed maturation and crop residue after crop harvest. All amendments and cover crop seeds were broadcast and spread by hand to ensure uniformity of application. Compost feedstock was primarily poultry litter and wood chips (2% N, C:N ratio = 12.5), and was spread at a rate of 22.4 $Mg\,ha^{-1}$ per application. Planting beds in both the AC and OST systems were prepared using strip tillage to create

Table 1. General management timeline for the ten treatments in the field study. For a complete management description, see Jacobsen and Jordan[12].

Cropping system	Treatment	October	November to March	April	May	June	July	August	September
Alley cropping	AC1	RC, CC		RC, ST	PT	W, P	H,W	H, P	H
	AC2	RC, CC		RC, ST	PT	W, M, P	H,W	H, P	H
	AC3	RC, CC		RC, ST, CP	PT	W, P	H,W	H, P	H
	AC4	RC, CC		RC, ST, CP	PT	W, M, P	H,W	H, P	H
	AC5	RC, CC, CP		RC, ST, CP	PT	W, P	H,W	H, P	H
	AC6	RC, CC, CP		RC, ST, CP	PT	W, M, P	H,W	H, P	H
Organic strip till	OST1	RC, CC		RC, ST	PT	W, M	H,W	H	H
	OST2	RC, CC		RC, ST, CP	PT	W, M	H,W	H	H
	OST3	RC, CC, CP		RC, ST, CP	PT	W, M	H,W	H	H
Conventional	CT	RC		CT, ST	PT	W	H,W	H	H

Abbreviations for management activity: CC, cover crop planting; CP, compost application; CT, conventional tillage; H, harvest; M, straw mulch application; P, hedgerow pruning; RC, roller crimping; ST, strip tillage; W, weeding.

Table 2. Fixed costs for a 40 ha (100 acre) farm. Total fixed farm costs per hectare are calculated for 4 ha (10 acres) in production.

Item	Details	New cost (US$)	Salvage value (US$)	Life span (years)	Cost per year (US$)
Tractor	40 hp, 4 wd	16,000	1600	10	1440
Roller crimper	120 cm wide	800	80	15	48
Rototiller	120 cm wide	2000	200	15	120
Bale spear		250	25	15	15
No-till rig	30 cm discs, 5 cm shanks	1500	150	15	90
Irrigation pump	5 hp	800	80	5	144
Piping	7.5 cm, buried	1200	0	10	120
Land rent cash value	1 ha irrigated vegetable rent yr^{-1}				305
Total whole farm cost (US$ ha^{-1})					799

two planting furrows per bed 45 cm apart, with 90 cm between each bed. All vegetables were drip irrigated, and were either direct seeded (Years 1 and 3) or transplanted by hand (Year 2) approximately 2 weeks after cover crop termination. Once weeds began to emerge from the cover crop residue layer, generally 4–8 weeks from planting, plots were hand weeded and a 2.5 cm thick layer of wheat straw (Year 1) or pasture hay (Years 2–3) was applied as mulch to designated treatments. Weeding continued as needed throughout the summer.

The timing of CT treatments was similar, with tillage conducted at the same time as spring roller crimping in the other treatments. Fertilizer was applied by hand as a side dressing in bands adjacent to crop plants according to the University of Georgia Cooperative Extension fertilizer guidelines for specific crops[17–19] at the time of planting. Inorganic fertilizer was used on the CT plots only. Herbicides and pesticides were not used on any of the plots. Thus, the input costs for the CT plots are an underestimate, since conventional farmers presumably would use these inputs. However, labor costs may be overestimated, as time spent weeding CT plots would have been lower than if an herbicide were used.

Costs and returns

Fixed farm costs are presented in Table 2, and were calculated for 4 ha of production. Fixed farm costs included only equipment used in this work, and assumed straight-line depreciation and 10% salvage value. The small-scale no-till rig used in this work was fabricated by the University of Georgia machine shop, and consisted of a series of two discs followed by a 10 cm sweep. This cost was not reflective of a no-till seed drill or other commercially available no-till equipment, but could be representative of a rig appropriate for small-scale diversified operations in the region. Fixed farm irrigation costs included a pump and infrastructure for the drip irrigation system. Land rent cash value was an average paid for irrigated vegetable production in the state of Georgia in 2007[20].

While the site was not certified organic, it was organically managed and production costs reported here were for USDA Certified Organically approved materials. They did not include the cost of organic certification or record keeping. Budgeting periods for each crop began with the sowing of the winter cover crop seed in October of the fall preceding the summer crop and ended with the final harvest

Table 3. Production input costs for a 3-year vegetable crop rotation in alley cropping (AC), organic strip-tillage (OST) and conventionally tilled cropping systems. Input quantities and prices are calculated on a per hectare basis.

Inputs	Input rate, AC systems	Input rate, CT and OST systems	Unit price, organic (US$)	Unit price, conventional	AC cost (US$)	OST cost (US$)	Conventional cost (US$)
Cover crop seed							
Austrian winter pea	35 kg	40 kg	2.40 kg^{-1}		84	96	
Crimson clover	17 kg	20 kg	6.60 kg^{-1}		112	132	
Rye	46 kg	54 kg	2.50 kg^{-1}		115	135	
Total cover crop cost					311	363	
Crop seed							
Cayenne pepper	200 g	300 g	0.50 g^{-1}	0.50 g^{-1}	100	150	150
Okra	3.5 kg	5 kg	110 kg^{-1}	4.40 kg^{-1}	385	–	22
Corn 'Ried's yellow dent'	6.2 kg	9 kg	27.70 kg^{-1}	5.5 kg^{-1}	172	250	50
Butternut squash	0.84 kg	1.26 kg	73.70 kg^{-1}	49.28 kg^{-1}	62	93	62
Total cost, corn and squash intercrop					234	343	112
Drip irrigation							
Connectors	144 connectors	174 connectors	0.35 $connector^{-1}$		50	61	61
Drip tape	14,4000 m	17,400 m	0.10 m^{-1}		1440	1740	1740
Total irrigation cost (US$ ha^{-1})					1490	1801	1801

of the summer crop. All costs and returns were calculated on a 1 ha scale, and accounted for a 25% loss of production land to hedgerows in AC treatments.

Production input costs

Production input costs that are consistent across all enterprises are presented in Table 3. Organic crop and cover crop seed prices reflect 2007 costs from the average price of three common organic farming supply sources, but did not include shipping and delivery charges. Estimates from the Georgia Vegetable Budgets[21] were used for conventional corn and okra seed costs. Conventional winter squash and pepper seed costs were the average price from three common farm supply sources for the region, as no data were found for the region with these figures. Irrigation costs for each crop included an annual purchase of drip tape, and a lifespan of mainline and connectors of 3 years. Connector and mainline costs were distributed evenly over 3 years.

Fuel costs for irrigation and tractor operations of each cropping system are presented in Table 4. Costs were based on an average diesel price of US$0.79 per liter and a fuel consumption rate of 3.8 liters h^{-1} for the 40 hp tractor and 1.9 liters h^{-1} for the irrigation pump. Lubrication costs were calculated as a standard 15% of fuel costs[22].

Fertility costs were treatment-specific and are presented in the enterprise budgets (Tables 6–8). Compost costs were calculated from the only organically approved compost provider in the state, and do not include delivery costs, as these would vary by distance from the supplier. Straw mulch costs were the local prices for an approximately 1 short ton round bale, delivery included. Costs for conventional fertilizers were based on estimates from the Georgia Vegetable Budgets[21].

Labor

Labor time for each task was recorded in every experimental plot (25–45 m^2) for the duration of the 3-year study, and the mean value for each treatment was converted to hours per hectare estimates. Due to the experimental nature of this work, practices such as the application of compost, fertilizer and hedgerow pruning, as well as seeding, weeding and harvest were all conducted by hand to ensure consistency in all plots. Labor for general, non-harvest operations were averaged over the 3-year experiment to reduce year-to-year variation (Table 5). A 15-min set-up time was assigned to each tractor operation (the average from this study) to allot for time spent changing equipment, refueling, etc., and spread evenly across all treatments that task was performed upon. Harvest and weeding labor were treatment-specific, and are presented in the enterprises budgets (Tables 6–8).

Labor arrangements on organic farms in the region are highly variable, consisting of family, paid farm workers, interns and volunteer labor under a heterogeneous blend of compensation schemes[9]. Rather than applying a standard hourly wage to the total labor (man) hours calculated for all operations, a US$10.00 per hour hired labor wage was included only when labor exceeded 80 h for any 7-day period throughout the season. This rationale was based on the 2004 survey results from the Organic Farming Research Foundation's (OFRF) National Organic Farmers Survey. The OFRF reported 67% of organic farmers worked on the farm full-time, with an average of two full-time, year-round

Table 4. Fuel costs for tractor and irrigation operations for each cropping system.

Cropping system	Alley cropping (AC)	Organic strip tillage (OST)	Conventional tillage (CT)
Tractor operations			
Operation time[1] (h ha^{-1} yr^{-1})			
CT	–	–	37
Roller crimping total (2 × spring, 1 × fall)	30	42	
Strip tillage	12	15	15
Total hours	42	57	52
Fuel use (liters ha^{-1} yr^{-1})	159	216	197
Annual tractor fuel cost[2] (US$)	145	197	179
Irrigation operations			
Irrigation time (h ha^{-1} yr^{-1})			
2005	30	–	10
2006	79	63	68
2007	118	100	98
Irrigation fuel use (liters ha^{-1} yr^{-1})			
2005	57	–	19
2006	148	121	129
2007	224	190	186
Irrigation fuel cost[2] (US$)			
2005	52	–	17
2006	135	109	117
2007	203	173	169
Total fuel cost (irrigation and tractor operations, US$ ha^{-1})			
2005	197		196
2006	280	306	296
2007	348	370	348

[1] Operation times were calculated as annual means from 3 years of operations.
[2] Fuel costs assume a gasoline price of US$3.00 gallon^{-1} plus 15% lubrication cost.

Table 5. General operations labor, hours per hectare, expressed as mean values from 2005 to 2007.

Operation	AC	OST	CT
Compost application (per event)	22	35	–
CT	–	–	37
Cover crop sowing	7	10	–
Fertilizer application	–	–	37
Hedgerow pruning (per event)	22	–	–
Hedgerow pruning application (per event)	22	–	–
Irrigation installation	15	20	20
Roller crimping total (2 × spring, 1 × fall)	30	42	–
Straw mulch application (AC2, AC4, AC6 and OST1-3)	72	49	–
Strip tillage	12	15	15

household employees. Our hired labor costs were thus an estimated net of the 80 h weekly family labor limit, derived under the assumption that each full-time household on-farm employee would work 40 h per week. In reality, most farmers would elect to work more than 40 h week^{-1} person^{-1} to the greatest extent possible. Thus our labor values were likely to be overestimates of labor costs on such a farm. Labor and production costs did not include marketing costs.

Yields and returns

Organic crop prices for okra (Table 6), hot pepper (Table 7) and winter squash (Table 8) are the average of market prices from three organic farms in the Athens, Georgia area and a certified organic market in Atlanta, Georgia, the nearest major metropolitan market. The organic corn price was an average value for No. 2 yellow corn from nine nationwide markets reported on the New Farm Organic Price Index[23] for the 2007 crop. Conventional prices for okra and corn were prices reported in the University of Georgia Vegetable Budgets[21]. No prices for conventional winter squash or hot pepper were found for the state. Instead, winter squash and cayenne pepper prices from the Louisiana State University Research and Extension Ag Center[24] were used.

Table 6. Enterprise budget for okra, grown in degraded soil in Georgia Piedmont.

	AC						
Inputs	**With winter cover crop (AC1)**	**AC1 + straw mulch (AC2)**	**AC1 + spring compost (AC3)**	**AC1 + spring compost + mulch (AC4)**	**AC1 + fall and spring compost (AC5)**	**AC1 + fall and spring compost + mulch (AC6)**	**CT**
Harvest materials costs (US$ per hectare)							
Seed (crop and cover crop)	696	696	696	696	696	696	22
Straw mulch	–	38	–	38	–	38	–
Nutrients (compost or fertilizer)	–	–	764	764	1527	1527	339
Irrigation supplies	1490	1490	1490	1490	1490	1490	1801
Fuel (irrigation and tractor operations)	197	197	197	197	197	197	196
Fixed costs	799	799	799	799	799	799	196
Total harvest materials cost	3182	3220	3946	3984	4709	4747	2554
Labor (h ha^{-1})							
Non-harvest labor (Table 4)	217	217	217	217	217	217	106
Crop planting (spring)	84	82	79	86	86	86	89
Weeding (summer, throughout)	235	333	234	356	316	331	879
Total non-harvest labor	536	632	530	659	619	634	1074
Payroll detail (annual, per hectare)							
Farm household employee non-harvest labor (h)	536	632	531	657	620	632	1074
Hired employee non-harvest labor cost[1]	0	0	0	0	0	0	480
Total non-harvest labor cost (annual)	0	0	0	0	0	0	480
Total harvest labor hours	731	682	741	699	580	692	608
Total harvest labor cost[1]	0	0	0	0	0	0	0
Total costs (materials and labor)	3182	3220	3946	3984	4709	4747	2554
Returns							
Okra (kg ha^{-1})	3946	4013	3382	3858	4369	4511	2602
No. of units (6.8 kg = ½ bushel unit)[2]	580	590	497	567	643	663	383
Price (US$ ½ bushel^{-1})	30	30	30	30	30	30	7
Gross returns (US$ ha^{-1})	17,400	17,700	14,910	17,010	19,290	19,890	2681
Net returns (US$ ha^{-1})	14,218	14,480	10,964	13,026	14,581	15,143	127

[1] Labor costs based on $10.00 hourly wage.
[2] Typical marketing unit = ½ bushel.

Identifying dominant, preferred production methods

Our study employed a stochastic dominance analysis model to evaluate the risk and return structures of the ten treatments in this work over the course of the 3-year study. Stochastic dominance analysis is a risk-efficiency criterion for determining the risk-efficient set of alternatives available to producers when faced with uncertain outcomes. More than just examining the return structures of (or level of payoffs from) different production alternatives, the stochastic dominance framework evaluates trade-offs between such levels and variability (riskiness) of the payoff variable.

Stochastic dominance is a useful, appropriate tool for analyzing decisions in agriculture, as outcomes of production decisions and methods can be influenced by a wide range of risk factors (such as weather, climate and pests). In making production decisions, a farmer thus must not rely solely on absolute figures, such as average yields or total net farm incomes, as these could be misleading and thus produce less optimal decisions. Specifically, without accounting for risk or variability, a farmer may quickly consider a specific production alternative as already adequately profitable merely based on a high average yield result. The stochastic dominance approach looks beyond total and average values, and also considers the variability of the year-to-year (or seasonal) production conditions that produce such figures. This approach helps farmers determine more favorable production alternatives that could ensure more stable or less risky outcomes.

The risk component of this analysis recognized that uncertainty, which is especially a significant factor in farming situations, can affect realization of payoff. Thus, a decision-maker evaluates trade-offs between higher payoffs and lower risk, with the choice determined by his/her level of risk aversion. In this study, the application of the model and the stochastic dominance framework allows for a ranking of alternatives based on producers' risk preferences for the most risk-efficient set of yields and returns to management.

Table 7. Enterprise budget for hot pepper, grown in degraded soil in Georgia Piedmont.

	AC						OST			
Inputs	**With winter cover crop (AC1)**	**AC1 + straw mulch (AC2)**	**AC1 + spring compost (AC3)**	**AC1 + spring compost + mulch (AC4)**	**AC1 + fall and spring compost (AC5)**	**AC1 + fall and spring compost + mulch (AC6)**	**Winter cover crop + mulch (OST1)**	**OST1 + spring compost (OST2)**	**OST1 + spring and fall compost (OST3)**	**CT**
Harvest materials costs (US$ per hectare)										
Seed (crop and cover crop)	411	411	411	411	411	411	513	513	513	150
Straw mulch	–	38	–	38	–	38	38	38	38	–
Nutrients (compost or fertilizer)	–	–	764	764	1527	1527	–	764	764	614
Irrigation supplies	1490	1490	1490	1490	1490	1490	1801	1801	1801	1801
Fuel (irrigation and tractor operations)	425	425	425	425	425	425	306	306	306	306
Fixed costs	799	799	799	799	799	799	799	799	799	799
Total harvest materials cost	3125	3163	3889	3927	4652	4690	3457	4220	4984	3670
Labor ($h\,ha^{-1}$)										
Non-harvest labor (Table 4)	217	217	217	217	217	217	205	205	205	106
Crop planting (spring)	217	210	230	217	222	217	309	309	309	309
Weeding (summer, throughout)	494	277	425	245	445	237	57	40	49	371
Total non-harvest labor	928	704	872	679	884	671	571	759	563	786
Payroll detail (annual, per hectare)										
Farm household employee non-harvest labor (h)	955	704	872	679	884	672	571	553	561	785
Hired employee non-harvest labor cost[1]	0	0	0	0	0	0	0	0	0	0
Farm household employee harvest labor (h)	496	398	422	435	348	412	210	348	483	257
Hired employee harvest labor (h)	64	0	0	77	62	109	371	227	183	30
Hired employee harvest labor cost[1]	640	0	0	770	620	1090	3710	2270	1830	300
Total costs (materials and labor)	3765	3163	3889	4697	5272	5780	7167	6490	6814	3970
Returns detail										
Peppers ($kg\,ha^{-1}$)	5832	5532	6373	3764	5697	3204	3798	4542	4846	3424
Price ($US\$\,kg^{-1}$)	6.60	6.60	6.60	6.60	6.60	6.60	6.60	6.60	6.60	6.60
Gross returns ($US\$\,ha^{-1}$)	38,491	36,511	42,061	24,842	37,600	21,146	25,067	29,977	31,983	22,598
Net returns ($US\$\,ha^{-1}$)	34,726	33,347	38,172	20,145	32,328	19,287	17,900	23,487	25,169	18,628

[1] Labor costs based on $10.00 hourly wage.

Table 8. Enterprise budget for corn and winter squash intercrop grown in degraded soil in Georgia Piedmont.

	AC						OST			
Inputs	**With winter cover crop (AC1)**	**AC1 + straw mulch (AC2)**	**AC1 + spring compost (AC3)**	**AC1 + spring compost + mulch (AC4)**	**AC1 + fall and spring compost (AC5)**	**AC1 + fall and spring compost + mulch (AC6)**	**Winter cover crop + mulch (OST1)**	**OST1 + spring compost (OST2)**	**OST1 + spring and fall compost (OST3)**	**CT**
Harvest materials costs (US$ per hectare)										
Seed (crop and cover crop)	334	334	334	334	334	334	706	706	706	112
Straw mulch		38		38		38	38	38	38	
Nutrients (compost or fertilizer)			764	764	1575	1575		764	1575	811
Irrigation supplies	1490	1490	1490	1490	1490	1490	1801	1801	1801	1801
Fuel (irrigation and tractor operations)	493	493	493	493	493	493	370	370	370	348
Fixed costs	799	799	799	799	799	799	799	799	799	799
Total harvest materials cost	3116	3154	3880	3918	4729	4729	3714	4138	1829	2251
Labor (h ha ^{1})										
Non-harvest labor (Table 4)	217	217	217	217	217	217	249	249	249	129
Crop planting (spring)	141	128	133	131	106	131	146	146	146	69
Weeding (summer, throughout)	190	111	183	128	141	133	25	32	20	198
Total non-harvest labor	548	266	533	476	464	481	420	247	415	496
Payroll detail (annual, per hectare)										
Farm household employee non-harvest labor (h ha^{-1})	548	457	531	474	464	482	373	383	368	373
Hired employee non-harvest labor cost[1] (US$ ha ^{1})	0	0	0	0	0	0	0	0	0	0
Farm household employee harvest labor (h ha^{-1})	47	52	37	49	37	119	32	22	44	49
Hired employee harvest labor cost[1]	0	0	0	0	0	0	0	0	0	0
Total hired labor cost	0	0	0	0	0	0	0	0	0	0
Total costs (materials and labor)	3116	3154	3880	3918	4729	4729	3714	4138	1829	2251
Returns detail										
Winter squash (kg ha^{-1})	1191	1806	1097	2509	1599	2928	3112	2536	3640	2480
Price (US$ kg ^{1})	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	0.73
Corn (bushels ha^{-1})	27	52	64	32	27	27	27	42	27	7
Price (US$ bushel^{-1})	11	11	11	11	11	11	11	11	11	3.50
Gross returns (US$ ha^{-1})	2262	3552	2514	4492	2935	5128	5432	4646	6303	1835
Net returns (US$ ha^{-1})	−854	398	−1366	574	−1794	399	1718	508	4480	−416

[1] Labor costs based on $10.00 hourly wage.

Researchers have developed multiple variations of stochastic dominance, but its two basic criteria are first- and second-degree stochastic dominance. We employed second-degree stochastic dominance analysis, which eliminates dominated or inefficient distributions from the first-degree stochastic dominance set[25]. This was accomplished by adding the assumption of risk aversion to the decision-making process with respect to the farmer or land managers' preferences.

Risk-averse agents seeking to maximize utility would never prefer a dominated distribution[26]. Therefore, a second-degree stochastically efficient set of alternatives would be comprised of only non-dominated distributions, and any further reduction of this set would require additional assumptions concerning risk preferences[26].

This analysis ranked the risk and return efficiencies of the ten treatments based on the following parameters:

1. Production yields: this measure isolated the production efficiency from other factors that can affect the risk and return profiles of the production methods. In order to standardize yields across all years and reduce variation, this analysis used the proportion (percent) of the experimental yields to conventional yield estimates for Georgia[27], instead of the absolute yield. Yields for the first year were based on a conventional okra yield of 10,946 kg ha^{-1} (325 bushels acre^{-1}); Year 2 yields were based on average conventional cayenne pepper yield of 10,105 kg ha^{-1} (9000 lbs acre^{-1}); and Year 3 yields were based on a 50% corn/50% winter squash planting area distribution assumption, with an average corn yield of 3.9 Mg ha^{-1} (62.5 bushels acre^{-1}) and average squash yield of 3521 kg ha^{-1} (112 bushels acre^{-1}).
2. Net returns per man hour of family labor: the combined effects of production and cost efficiencies are captured by this measure of net return. Profitability is also related to the variable rates of labor intensiveness of the different production methods by calculating the net return per man hour of residual family labor invested in farm work that supplemented the assumed hired labor requirements. This measure thus represented the farm owner's family's compensation for their collective labor hour-investment in the farm operations.

Results and discussion

As discussed previously, budgetary information for organic, conservation tillage systems with which to compare our results was sparse. Some yield and production cost information existed for either organic production or conservation tillage, but rarely both. The few exceptions found used living mulches interplanted with organically managed vegetables[28–30]. Although yields were not statistically different between treatments due to high variation within treatments[12], the resulting differences in returns may be of economic significance to the farmer.

Experimental yields were consistently extremely low compared to conventional production estimates for the state. All yield data in this study must be interpreted in the light of the degraded soils in which the experiment took place. The soils in this study were a highly eroded Pacolet sandy clay loam that was devoid of an A horizon and largely consisted of the B (subsoil) horizon. The site was chosen, because it was the worst soil on the experimental farm, and is characteristic, if not worse, than the sandy clay loams commonly found in the region. Additionally, each crop was only grown for one year in the rotation, and thus yields may not be representative of long-term yield potential. Okra yields were in the 'worst production category'[31], and corn was 14% of the average yield for strip tilled corn in South Georgia[32], after accounting for the production area occupied by winter squash. In addition to the degraded soil on the site, a severe drought in 2007 limited the germination of the heirloom corn variety used in this work that was not treated with fungicide or drought tolerant. Although the yields were lower than conventional averages for the state, okra and hot pepper yields were comparable to experimental yields in an organically managed, conservation tillage experimental study in the Midwest[29].

Organic okra and hot pepper production had the highest net returns to management, although the harvest labor requirements for these crops were 10–15-fold higher than the corn/winter squash intercrop. Both okra and hot pepper are high-yielding, labor-intensive crops, the former with a significant organic price premium. Okra production did not require additional hired labor for any of the treatments, but the hot pepper did require additional harvest labor. However, the greater returns to management justified the expense of hired harvest labor.

Previous research in the region suggested that AC may be best suited to high-value horticultural crops due to higher labor and land requirements needed to manage the hedgerows[11]. However, the labor associated with hedgerow management averaged only 30 h pruning event^{-1} ha^{-1}. This time included the precise application of residues for experimental purposes, and was probably an overestimate of actual labor requirements.

Mulches are frequently used in organic farming systems to suppress weeds, control erosion and retain soil moisture. In 2005 and 2006, mulched AC treatments required 23% less labor than non-mulched treatments, due to effective weed suppression. In 2007, mulch only reduced labor requirements by 4%, due to a lack of weed pressure in the extreme drought. All the OST treatments received mulch; thus, mulched versus non-mulched labor requirements could not be compared in this system. Although mulch applications generally reduced weeding requirements, they also resulted in significantly lower soil carbon levels than non-mulched treatments receiving the same level of compost (Table 9). In the hot, subtropical climate of the southeastern US, evapotranspiration rates in the summer are high and soils dry down rapidly. Increased soil moisture under mulch could have led to increased decomposition rates of organic amendments and soil organic matter in

Table 9. Changes in total soil carbon levels over the course of the accompanying field study. For complete discussion and presentation of results, see Jacobsen and Jordan[12].

Method	Year 1		Year 3		
	Mean total soil carbon ($Mg\,ha^{-1}$)	Standard deviation	Mean total soil carbon ($Mg\,ha^{-1}$)	Standard deviation	Change in total soil carbon ($Mg\,ha^{-1}$)
AC with winter cover crop (AC1)	14.2	4.0	11.4	2.0	−3.8[2]
AC1 + straw mulch (AC2)	19.3	4.0	9.6	1.2	−9.8[2]
AC1 + spring compost (AC3)	14.0	4.3	15.3	4.6	1.3
AC1 + spring compost + mulch (AC4)	14.6	3.6	12.0	5.8	−2.6[1]
AC1 + fall and spring compost (AC5)	13.6	3.3	17.1	4.7	3.5[2]
AC1 + fall and spring compost + mulch (AC6)	14.1	0.9	11.4	1.9	−2.7
Organic strip tillage with winter cover crop + mulch (OST1)	9.6	1.6	7.6	1.1	−2.0
OST1 + spring compost (OST2)	10.3	0.8	9.0	1.0	−1.3
OST1 + spring and fall compost (OST3)	9.0	0.5	8.3	1.0	−0.7
CT	12.8	2.2	10.1	1.2	−2.7[2]

[1] Indicates significant change between Year 1 and end of Year 3 at the $P \leqslant 0.10$ level.
[2] Indicates significant change between Year 1 and end of Year 3 and the $P \leqslant 0.05$ level.

mulched treatments; thus, decreased labor requirements also decreased potential environmental benefits to the system (for a complete discussion of the soil carbon dynamics in this work, see Jacobsen and Jordan[12]).

Additionally, mulched treatments had inconsistent effects on yields in the 3 years. Okra, corn and winter squash yields in the mulched treatments were higher than non-mulched treatments receiving the same level of compost. These crops benefited from the increased moisture under the mulch, as the okra is fungal-disease resistant and the corn and winter squash were grown in a drought year. However, the increased moisture under the mulch led to an outbreak of *Fusarium* wilt in the pepper plants in mulched treatments, decreasing yields. This indicates that mulch in addition to the roller crimper killed cover crop residue may be best suited for dry years and for plants that are not susceptible to soil-borne pathogens.

The effects of compost additions were less straightforward and were highly variable in this relatively short study period. The greater compost application rate ($44.8\,Mg\,ha^{-1}$) did not have consistently greater yields than treatments with $22.4\,Mg\,ha^{-1}$ or no compost. This indicates that the ecological interactions in restorative agroecosystems on degraded soils are more complicated than what would be predicted by simply adding more amendments. Generally, the organic treatments had higher yields than the conventional treatment. When accounting for organic price premiums, the organic treatments had consistently higher net returns to management than the conventional treatment.

Treatments AC2, OST2, OST1 and AC3 had the highest net returns per family labor man hour. In this analysis, the first three of these four treatments had the lowest labor requirements due to the presence of mulch, which suppressed weeds and reduced weeding labor. Additionally, these treatments ranked in the top four in net returns, exclusive of labor costs (Table 10). Altogether, the reduction in labor and high net returns produced better risk-efficiency rankings for these alternatives in terms of net returns to family labor (Table 11). The existing literature presents contrasting results regarding the profitability of organic farming systems when considering both the increased labor requirements and organic price premiums. Some have claimed that reduced input costs, high price premiums and endurance under drier conditions have enhanced organic farms' relative profitability[33,34]. Other studies, however, have contested the advantage due to higher labor costs. As reviewed by Friedman[35], the production costs of organic apples in California were 10–25% higher than conventional farms as a result of higher material and labor costs. In contrast, in a potato study in Idaho involving 18 conventional and organic farming systems, the average material costs were lower among organic farms while labor costs were higher. In this study, the stochastic dominance analysis of the net returns to family labor parameter ranked most of the organic systems consistently higher than the conventional system on this highly degraded soil.

Although the year-to-year variation was important for understanding the utility of each system and certain production practices to specific enterprises, the stochastic dominance analysis allowed us to assess variations in system performance over time. These results can be compared with ecological parameters across all enterprises. Treatments AC3 (AC + $22.4\,Mg\,ha^{-1}\,yr^{-1}$ compost), AC2 (AC + mulch), OST2 (OST + $22.4\,Mg\,ha^{-1}\,yr^{-1}$ compost + mulch) and OST3 (OST + $44.8\,Mg\,ha^{-1}\,yr^{-1}$ + mulch) ranked highest in proportional yields across all

Table 10. Derivation of net return per hour of family labor. Derivations were based on raw data from individual plots across the three crops (okra, hot pepper and corn/winter squash intercrop) grown in the study. Variation reflects differences in labor requirements and net returns between the three enterprises.

	Net returns, excluding labor costs (US$ ha^{-1})		Labor requirements (h ha^{-1})		Net returns per hour of family labor (US$ ha^{-1})	
Treatment	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**
AC with winter cover crop (AC1)	17,387.57	19,675.08	810.48	467.03	35.10	43.52
AC1 + straw mulch (AC2)	17,453.29	19,929.94	659.81	333.82	49.10	57.77
AC1 + spring compost (AC3)	19,736.93	24,429.93	756.76	414.22	39.52	59.23
AC1 + spring compost + mulch (AC4)	10,876.00	13,229.49	749.65	379.76	28.16	3351.80
AC1 + fall and spring compost (AC5)	11,612.88	18,535.45	739.77	413.53	24.13	48.44
AC1 + fall and spring compost + mulch (AC6)	8629.69	12,371.19	799.66	355.51	24.53	39.62
Organic strip tillage with winter cover crop + mulch (OST1)	11,621.89	17,660.52	623.38	496.15	40.56	44.02
OST1 + spring compost (OST2)	14,791.00	20,889.21	648.38	461.45	44.81	71.51
OST1 + spring and fall compost (OST3)	13,438.58	16,396.43	725.56	487.58	36.95	54.66
CT	2390.39	6800.55	699.33	340.71	3.26	22.21

Table 11. Stochastic dominance results based on production yields, revenues and changes in soil carbon levels. Rankings are expressed from low to high, where 1 is the most dominant (preferable) and 10 is the least.

	Percent of average crop yields[1]		Net return/family labor man hour (FLMH)		Stochastic dominance rankings	
Method	**Mean**	**Standard deviation**	**Mean (US$ ha^{-1})**	**Standard deviation**	**Yield**	**Net return/ FLMH**
AC with winter cover crop (AC1)	40	20	35	44	5	6
AC1 + straw mulch (AC2)	45	20	49	58	2	1
AC1 + spring compost (AC3)	46	30	40	59	1	4
AC1 + spring compost + mulch (AC4)	36	13	28	34	7	7
AC1 + fall and spring compost (AC5)	33	22	24	48	9	9
AC1 + fall and spring compost + mulch (AC6)	35	16	25	40	8	8
Organic strip tillage with winter cover crop + mulch (OST1)	38	25	41	44	6	3
OST1 + spring compost (OST2)	44	29	45	72	3	2
OST1 + spring and fall compost (OST3)	42	23	37	55	4	5
CT	21	13	3	22	10	10

[1] To standardize across yields for different crops, yields are expressed as a percentage of average conventional yields. Proportional yields are based on the following average conventional yields per hectare: 10,946 kg ha^{-1} (325 bushels acre^{-1}) of okra (Year 1), 10,105 kg ha^{-1} (9000 lbs acre^{-1}) of cayenne pepper (Year 2) and a 50/50 acreage allocation with 62.7 kg ha^{-1} (62.5 bushels acre^{-1}) of corn and 3521 kg ha^{-1} (112 bushels acre^{-1}) of squash (Year 3).

years, but averaged only 42–45% of the statewide average[27] (Table 11). These four treatments also produced the most risk-efficient yield structures, given their stochastic dominance rankings.

AC3 and AC5 (AC + 44.8 Mg ha^{-1} mulch yr^{-1}) were the only treatments with net increases in soil carbon over the course of the 3-year study, although the latter was the only treatment with a significant increase. It is important to note that appreciable changes in soil carbon levels requires long-term study, and that soil carbon results presented in this work can be considered indicators of trends, but not definitive, long-term data. However, these results suggested that in highly degraded soils in the subtropics compost additions may be necessary to build soil carbon levels even in systems incorporating winter cover crops and perennial legumes. In addition, while the absence of mulch increased weeding labor, only treatments without mulch increased in soil carbon in the AC system. These results demonstrate that while a few treatments may be preferable for a single parameter, no treatment emerged as dominant for all parameters. However, the AC treatment receiving 22.4 Mg ha^{-1} yr^{-1} (AC3) ranked in the top four for all

parameters in the stochastic dominance analysis, had significant increases in soil carbon levels and required very little additional labor for hedgerow management, as previously discussed.

Conclusions

Organic farming and other ecological approaches to agriculture employ long-term systems approaches to nutrient and pest management. These systems frequently incorporate the use of winter cover crops, fallow periods and organic amendments to increase soil organic matter and thus increase the long-term productive capacity of the soil[36]. The goal of this work was to gain a general understanding of the economic costs and benefits of experimental agroecosystems designed to restore highly degraded soils in the Georgia Piedmont using a suite of these techniques in combination.

The organic conservation tillage treatments had less tractor and labor costs than the tillage-intensive conventional treatment. The application of mulches effectively suppressed weeds and reduced weeding labor requirements by an average of 23% during non-drought years. However, the presence of mulch increased the decomposition of compost and soil organic matter in this 3-year study, highlighting the need for longer term research on potential soil carbon sequestration benefits of organic conservation tillage-based systems. Yields in all experimental treatments were lower than in conventional studies found for the region. This was expected due to the nature of the soil at the study site, which had been abandoned for conventional row crop production due to lack of productivity for a number of years. However, returns on high-labor, organic crops were over US$30,000 ha^{-1} in some treatments. Our stochastic dominance results demonstrate that no one treatment maximized yields, net returns per family hour of labor or soil carbon increases. However, when these parameters were viewed together, AC systems receiving 22.4 $Mg\,ha^{-1}\,yr^{-1}$ of compost were an optimal risk-efficient choice for all parameters and demonstrated significant gains in soil carbon, a key management challenge in the region. These results indicate that some organic, conservation tillage systems could restore soil productivity and command high returns per land area across multiple enterprises, allowing land to remain in cultivation while improving soil quality.

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Using focus groups to assess almond growers' plant nutrition information needs

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Abstract

University of California (UC) scientists have established critical values (CVs) for almond production, but the nutritional information the CVs provide may be outdated and insufficient. In December 2006, researchers at UC Davis conducted focus group interviews with a sample of stakeholders in California's almond industry. The focus groups were designed to collect information relating to factors affecting growers' nutrition decisions, priorities in education and research relating to plant nutrition, and expected consequences of environmental regulation for the industry. Stakeholders identified problems with the CVs and voiced concern about the future of the almond industry in light of impending environmental regulations. Many stakeholders identified university research as a way to protect the industry by providing strong, recent scientific data on which nutritional limits and environmental regulations can be based. The focus groups served as a useful research method for obtaining detailed information about stakeholders' motivations and priorities and also for informing a quantitative follow-up survey that was subsequently mailed to a larger population of Californian almond growers.

Key words: focus groups, almond, critical values, nutrition

Introduction

Critical values (CVs) describe the nutrient levels in plant tissues at which plants begin to show deficiency symptoms. University of California-established CVs (UC CVs) for determination of almond nutrient status and the methods used to manage fertilization in almonds may be outdated; specifically, UC recommendations may not adequately reflect the significant changes in orchard management, fertilizer formulations and application technologies or the increasing demands for environmental stewardship that have occurred in the almond industry in recent years. The research conducted from the 1950s through the 1980s has not been adequately re-examined in recent years and has not been adapted to the modern production context, and laboratory methodologies have not kept pace with advances in extraction procedures and analytical techniques[1]. Efforts to develop best management practices (BMPs) for nitrogen management in almonds have been hampered by an inadequate research base and by the state's diversity of almond growing conditions, which make identifying best practices difficult. In the absence of viable and well-regarded standards and guidelines for nutrient management, growers may not have the resources needed to use fertilizers wisely.

In addition to being possibly outdated, the UC CVs may be limited in their practical application because they measure nutrient deficiency rather than nutrient status associated with yield optimization, and it is widely accepted that the appearance of visual symptoms of nutrient deficiencies occurs only after growth and productivity have been negatively impacted[2]. While this approach to nutrient management may have been appropriate in the past, given difficulties in conducting large-scale yield-based experiments and given the nature of production systems at the time of experimentation; modern production systems and awareness of the environmental impacts of poor fertilization practice may require that nutrients be managed more precisely to eliminate any potential negative impact on plant establishment, yield and the environment.

There is a good deal of uncertainty about current practices and standards for plant nutrition in almond production. Further, there has not been a significant review of the 'state of the industry' and no meaningful consideration of where future investment of educational, outreach, or research activities should be directed in the field of plant

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nutrition for almonds. In an effort to fill this information gap, researchers from the University of California, Davis (UC Davis), with the support of the Almond Board of California and the California Department of Food and Agriculture, decided to investigate almond growers' current fertilization practices, factors influencing their fertilization decisions, and growers' priorities and concerns relating to future research and outreach programs.

A meaningful assessment of the current state of plant nutrition knowledge could not be conducted without a detailed consultation process, so we coordinated focus group interviews with industry stakeholders in order to identify current practices, concerns and needs in almond nutrition. The information collected from the focus groups was used to inform the content of a survey that was subsequently administered to a larger population of almond growers. With the data from the focus groups and survey, UC researchers hope to collate existing information and BMPs and design a new research and extension initiative to increase the efficiency of fertilizer usage and guide subsequent nutrition research and education programs.

Mail surveys are commonly utilized by university researchers and extension agents to investigate agricultural industries. Agricultural researchers have recently used mail surveys to pursue a variety of goals, from investigating the state of California's cattle industry in light of economic change[3] to assessing the pest management decision-making processes of almond, cotton and cranberry growers[4–6]. Interpretation of these survey results has allowed researchers to predict future industry trends, identify stakeholder needs and assess how future extension and research efforts can be tailored to meet these needs[3–6].

Despite the ease of their administration and the benefits of collecting data from many stakeholders in a single research effort, mail surveys do not always provide researchers with easily interpretable results. In Brodt et al.'s investigation of cotton growers[5], for example, researchers were unable to determine, based on questions about adoption of individual practices, whether growers exhibited multidimensional understandings of their farms as agro-ecosystems. The authors concluded that in-depth interviews would be a more useful tool than mail surveys to collect this type of information. Focus group studies, one of numerous qualitative methods gaining popularity among researchers in agricultural fields[7], allow skilled interviewers to obtain qualitative information from interviewees in discussions. The open-ended approach of focus groups allows interviewees to share experiences and attitudes, conveying their true thoughts and feelings while providing data that are of specific interest to the researcher[8]. Focus group interviews are used commonly in the social sciences by researchers at the exploratory stage of research, as a stand-alone research method or in combination with surveys or individual interviews[9].

Focus groups are a useful tool to rapidly and efficiently gather detailed opinions from stakeholders, and sessions can easily be carried out onsite at industry conventions or field days. As a method of interviewing stakeholders, focus groups can save researchers time as compared with individual interviews by allowing them to hear viewpoints of multiple interviewees in a single sitting. The group atmosphere of focus groups may also be of benefit to researchers because it allows interviewees to compare their views to those of others, often leading them to voluntarily change their opinions to align behind well-informed interviewees, thus increasing the likelihood of reaching consensus[10]. This trend can also be a danger to researchers, however, because there is a possibility of individuals being dominated by others in focus group exercises[10,11]. The results of focus groups are easy to interpret and provide researchers with the opportunity to listen to diverse viewpoints and perspectives developed through open-ended discussion, rather than limiting stakeholders to providing only certain types of answers to questions, as may occur in a survey. The results of focus groups may be used by researchers as the final step in information collection, or researchers may choose to use the information to inform a more quantitative process of data collection.

While focus groups are very useful at surfacing ideas and insights of those interviewed, the qualitative data gathered through this method only reflects those represented in the interviews, which is often very limited in number. The usefulness of focus group interviews, then, is to broadly paint a picture of what interviewees believe is or is not of importance. On the other hand, other social science research techniques, such as mail and internet surveys, allow researchers to select and sample and extrapolate findings to the population. Surveys allow researchers to gain insight into topics such as whether growers base their decisions more on environmental or economic considerations[6,12] and allow growers to express numerically the importance of specific survey items.

For our study of the almond industry's nutrition management practices and research needs, therefore, we used the information we gathered from the focus groups to inform a mail survey of 1800 randomly selected almond growers (the results of which are presented by Lopus et al.[12]). We based the mail survey question topics on the subjects raised by focus group interviewees, and for multiple-choice survey questions, answer choices were based upon the topics discussed in the focus groups. In this way, we were able to construct our mail survey to contain questions of relevance to industry stakeholders, since the subject matter had been discussed in the focus groups by other industry members. We intend to use the results of both research methods when designing a new research and extension initiative and developing subsequent nutrition research and education programs.

Methods

We conducted the focus group study at the Almond Industry Conference in Modesto, California in December 2006. The sample consisted of 34 almond growers,

nutrition consultants, farm advisors and members of the Almond Board from counties throughout California. Focus group interviewees were invited to take part based on the researchers' personal familiarities with growers and consultants who manage farms of various sizes and locations with diverse management practices. Krueger[13] suggests that focus groups should be homogeneous and should range in size from 4 to 12 participants to allow opportunity for individuals to talk and to provide for practical logistics and management. In this study, the three focus groups fell within this range, with 10 to 12 people participating in each group. Each group was roughly homogeneous in composition, comprised primarily of growers, nutrition consultants, or farm advisors, representatives from the California Environmental Protection Agency and representatives from the California Air Resources Board.

Three 90-min focus group sessions were conducted; by conducting three focus group sessions, we were able to detect patterns and trends across the groups and increase our chances for a saturated response[14], in which members of multiple groups voice the same idea. Since information was collected from only one of each group type, we do not have adequate samples to analyze across multiple groups of farmers, nutrition consultants, or farm advisors, and it is not possible for us to compare and contrast between stakeholder types. Only with multiple groups of each type would we know whether we reached saturation, the point at which the full range of ideas has been heard, and draw conclusions with some certainty[8]. Instead, when saturation was reached across the groups, we drew conclusions about stakeholders in general but not linked to stakeholder type.

Two UC researchers attended each focus group, with one moderating the interview, while the other took field notes. The researchers had attended a focus group training workshop and were familiar with topics in plant nutrition. Each focus group followed a format outlined by Krueger and Casey[8], and interview questions were structured around three areas: (1) factors affecting growers' nutrition decisions, including perceived usefulness of CVs and soil and tissue sampling; (2) priorities in education and research relating to plant nutrition; and (3) expected consequences of environmental regulation to the almond industry.

We followed Krueger and Casey's 'long-table approach' to data analysis for the focus groups[8], relying initially on field notes and supplementing our research with an audiotape-based analysis approach to fill in details. In accordance with the long-table method, we identified field notes with colors to indicate which group had provided the information, physically cut the notes apart, and placed the clippings of similar concepts together. When ideas came up repeatedly, we considered these themes to be of importance, and we structured our written report and survey questions around these themes[8]. Analysis of focus group data in this way is a proven and established procedure for collecting verifiable information about populations[8].

Results

Stakeholders identified three primary sources of information that growers depend upon when making decisions related to nutrition management. Interviewees in all focus groups identified universities and other farmers as important sources of information, but most stakeholders expressed that private nutrition consultants are many growers' first line of information. Although nutrition consultants may have superceded extension agents as the primary point of contact with many almond growers, complex relationships exist between growers, universities and nutrition consultants, since a private consultant's recommendation may be based upon UC research. In this way, research developed by the university may still be of great importance to the almond industry, even if the information it provides is disseminated to growers through a privately hired source.

When asked their opinions about the effectiveness of the UC CVs, interviewees in all focus groups expressed that the values are better than nothing and may provide a general guideline for nutrition management program (Table 1). The focus groups comprised primarily of growers and nutrition consultants talked at length about concerns with the accuracy of values and whether they are outdated, with one grower stating, 'Aren't there varieties now that weren't there thirty years ago? 'Cause that's when a lot of this stuff was developed'. Stakeholders confirmed our belief that the industry is concerned with the suitability of the CVs to inform modern nutrition management practices, questioning whether the values have kept up with changes in production related to yields and planting densities. The primary concerns interviewees expressed about CVs related to problems with timing, sampling method, yield maximization and nutrient interactions.

Stakeholders repeatedly cited timing as a limitation to using CVs to inform nutrient management decisions on orchards (Table 1). Interviewees were concerned that the CVs relate to nutrient levels in plant tissue during only a 10-day period in July. Although sampling is supposed to occur during this period to allow nutrient levels to be measured when they have reached a plateau, some interviewees were concerned with the accuracy of this sampling method, stating that weekly samples would be necessary to ensure the plateau had been reached. Another problem with the small sampling window is that information is not available for other times of the year, so growers find themselves 'flying blind' much of the time. Interviewees prioritized future research projects that would allow growers to measure nutrient levels during the time of the year between dormancy and leaf production. Other interviewees were concerned with misuse of the CVs by growers who sample in the wrong month. CVs were also thought to be of little use for those nutrients (e.g., Mn, Zn and Fe) in which deficiencies may stand out in other months (early spring) but look normal when tissue samples are collected in July.

Table 1. Topics addressed by each focus group (roughly divided as growers, industry members and Farm Advisors) when asked their opinions about the effectiveness of UC CVs. Accuracy of CVs, timing of tissue sampling, interactions affecting nutrients, specific nutrients, challenges with sampling methods and applying information, and development of personal CVs were discussed by members of all focus groups, indicating that 'saturation' was reached. Specific points raised by members of each focus group demonstrate the context in which the saturated topic was discussed. An 'x' indicates a sub-topic not recorded in the transcript of a particular focus group; however, since information was collected from only one of each group type for each study, it is not possible for us to compare and contrast between stakeholder types.

	Sample context in which topic was discussed by each focus group		
Saturated topic	**(A) Growers**	**(B) Industry members**	**(C) Farm advisors**
Accuracy of CVs	Don't think CVs are accurate	Don't think CVs are accurate	x
	CVs give guidance for some nutrients	CVs are better than nothing	CVs provide general guidelines
Timing of tissue sampling	Values are only for June and July	Year-round decisions must be based on values from the first 10 days of July	Deficiencies present in other months may not appear in July
Interactions affecting nutrients	CVs should consider nutrient interactions	Researchers should determine ratio of nutrients relative to each other for optimum growth	Researchers should assess how elements work with plants
	Production regime affects nutrient levels	Foliar versus other application methods affects nutrient levels	Research of other variables (such as the irrigation method) could lead to better understanding of how nutrients fluctuate
Specific nutrients	Concerned with potassium	People use more than the CV levels of potassium	Research trials showed that CVs aren't far off for potassium, but the industry disagrees. More trials needed
	Concerned with zinc: leaf analysis doesn't help	x	Can't use leaf analysis for zinc because of foliar applications and because zinc is not held in leaves
	Boron levels are questionable	x	In some orchards, boron CVs appear too high and in others they appear to be correct
Challenges with the sampling method and applying information	x	Values fluctuate: the same person taking a sample could get two different results	Growers and consultants may not recognize margin for error in lab analyses
	Unsure of how lab results relate back to CVs	x	Labs provide average values
	How do CVs tie in with yield maximization?	CVs aren't designed to maximize yields	x
Development of personal CVs	Some growers rely on consultants to give them information about CVs	Some labs use modified CVs or interpret CVs independently	Different labs have their own interpretations of the UC CVs

Another major topic of discussion of CVs related to the difficulties of accurately sampling plant tissue to measure nutrient levels (Table 1). In addition to problems with the timing of tissue collection, interviewees were concerned with sampling inaccuracies due to spatial variation across orchards or even within trees, creating the possibility that 'you could pick one[leaf] with your left hand and one with your right hand and get two different numbers'. Interviewees stressed that the small sample sizes relative to the size of the orchard mask variability, and growers or nutrition consultants may be unaware of the large margin of error associated with the lab results. If an orchard's number drops from one year to the next, growers and consultants may unnecessarily apply more fertilizer in the future, even if the change was not significant.

Many interviewees were also dissatisfied with the CVs' dependencies on average values (Table 1). As one farm advisor expressed, if the critical level for a tree is 2.2, a grower might aim for an average level of 2.5 across his orchard to ensure that few of his trees are below the critical level. As another farm advisor explained, 'If the average is 2.2, it's likely that there are some 2.0, and there are some 2.4'. Since an orchard-wide average of above a critical level may be associated with half of the orchard's trees falling below that critical level, interviewees felt there was a disconnection between tree-scale sampling and orchard-wide nutrition optimization. One nutrition consultant called tree replicates 'almost meaningless', and interviewees in all focus groups prioritized future research addressing tree variability and nutrient status on the landscape scale.

Many interviewees were unclear about how a grower could practically apply the information provided by CVs to an orchards' nutrition management program (Table 1). In cases of lab tests indicating nutrient deficiencies, it was unclear to some interviewees what steps should be taken to remedy the problem, and they questioned how lab results relate to the CVs. Interviewees questioned the best remedy for an orchard slightly deficient in a particular nutrient and highlighted this as an important field for future research. The relationship between CVs and yield maximization was also discussed. As one grower simply stated, 'Obviously, those levels show when you have symptoms, but they don't show what impact they have on yield, and that's the question a lot of people ask'. Growers are interested in optimizing their trees' performances, rather than managing their orchards just above a critical level.

In addition to citing the practical problems of timing, sampling and yield maximization when using CVs to inform nutrition management, interviewees in all focus groups were concerned that the established CVs ignore interactions between nutrients in an orchard (Table 1). Interviewees cited the importance of conducting high-yield research of multiple nutrients simultaneously to understand complex situations in which the CV for one element may depend upon the level of another element. Some interviewees suggested the development of ideal ratios between nutrients, since too much nitrogen can throw off an orchard's potassium balance, or a drop in zinc occurs with an increase in phosphorus. As one nutrition consultant expressed, it has been the industry's tendency to improve yields with the application of more nitrogen, 'but maybe if they'd added some other nutrient, the roots would have gone better, or more [nitrogen] would have been utilized, or something else'.

Concerns about interactions went beyond just those between nutrients in an orchard, and many interviewees expressed interest in research focusing upon relationships between plant nutrition and external factors such as fertilizer application method, soil type, propensity to disease and irrigation method (Table 1). Some interviewees believed that fertilizer use efficiency is closely related to the irrigation system, and water mobilizes the nutrients, but they would like to see more research on the topic. Questions about irrigation particularly focused on cases of micro and drip irrigation, in which roots grow closer to the surface than with other irrigation methods, causing one nutrition consultant to ask, 'If our technology has changed how the tree grows, should we be changing our application technique to go along with it?' Another consultant observed that

> There needs to be better education on what antagonizes, or what uses up. I mean, you put phosphorus on, your zinc goes down. You put boron on, your calcium goes in a different direction. You put more calcium on, your boron goes in a different direction.... We should be thinking in terms of more than just a single shot of calcium, a single shot of boron.

Implications

Lack of useful information and inadequate management of existing information are commonly cited barriers to adoption of sustainable practices in many agricultural settings[15], and California's almond industry also identified these factors as problems. Input from the focus group interviewees confirmed our beliefs that there are numerous uncertainties as to which nutrition management practices will optimize almond production. Without viable management standards providing growers with clear information about how to best balance yields, production costs and environmental considerations, many growers have responded by increasing the level of fertilizer they apply in order to avoid deficiencies. Expressed one grower,

> We have been farming with these fertilizers pretty hard. I will bet you if you looked at the amount of spray we have put on in the last 5 years, it is probably higher than at any time in the industry. And I think it is time to reevaluate that.

Interviewees expressed that when laboratories provide growers with average nutrient levels for trees in their region, growers may respond by trying to push their trees' levels higher in an effort to be better than average. The results of over-fertilization may have a negative economic effect on growers, if their improved yields do not meet the costs of increased fertilization inputs. Negative environmental effects could occur in surrounding communities, should the excess nutrients run off from farms or leach into groundwater.

Interviewees in all focus groups expressed concern about impending regulations on the almond industry, worrying that environmental pressures will be extreme. As one grower asked,

> Environmentally, what are those critical levels? Are we putting on excess nitrogen? Are we contaminating the groundwater? What are the optimum levels that we should be applying? We don't have the relationship between those and what yield is returned. All we have is 30- or 40-year-old data, and that's not adequate.

Interviewees feared that regulations based on the outdated values, which may not relate to modern cultivars, will 'handcuff the growers' and prevent them from being able to grow high-yielding crops. One farm advisor worried that when regulations are created, regulators will 'grab for the first thing on the shelf', which he described as a 'pretty sloppy' nitrogen budget. Currently, there are few sources of information related to almond nutrition management to help the industry address this problem.

Participants in all groups felt future university research provides a primary opportunity to ensure that environmental regulations on the almond industry will be based on viable nutrition management practices that will not seriously detriment the industry economically. As one nutrition consultant stated, 'Having strong data about what the nutrient needs of the trees are, under what conditions, ultimately can help us take a stronger stand, should the

push-back come'. Interviewees cited the University of California's obligation to look out for impacts to growers and felt the university should communicate the results of its future research projects with the Environmental Protection Agency. New research to bring 'scientific proof back into the picture' has the potential to inform growers of BMPs and to justify those practices, should environmental regulation occur. While it is beyond the scope of this paper to address discrepancies between focus group expectations and researcher roles, we will use the stakeholder opinions and priorities expressed in the focus groups to inform our roles as researchers in the context of broader obligations and capabilities.

> I mean, sometimes, we tend to over-farm our trees a little bit. We had a couple plots up on a hill earlier this year, and all those trees were just yellow for about a month. And I threw everything but the kitchen sink in, and finally I just quit, and then they just greened up on their own.
>
> –Grower

Recommendations

The results of the focus group discussions confirmed the existence of indicators that the UC CVs do not fully meet the almond industry's needs. Results demonstrated widespread concern among the almond industry about the relevance of CVs and the difficulties in applying the information they provide to an orchard's nutrition program.

Focus group interviewees prioritized a number of considerations for future research in almond nutrition management. While research for established CVs was based on single nutrients evaluated on a tree-wide scale, interviewees in the focus groups called for a systems-based approach to research in which interactions between nutrients and external factors are investigated on an orchard-wide scale. The established CVs are reductionistic by nature, but growers manage their orchards systematically and require a solution that allows laboratory results to clearly inform management practices.

An integrated approach to nutrition management research, in which investigators consider multiple elements and factors simultaneously on a large scale, will serve stakeholders in California's almond industry economically and environmentally. By identifying BMPs relating to modern cultivars and technology, researchers will provide growers with the opportunity to optimize yields without using excess fertilizer that does not provide adequate economic returns. The research will also serve to protect the industry when environmental regulations are adopted, giving stakeholders hard data with which to justify their fertilization practices. This focus group study demonstrated a clear and immediate need for a new approach to nutrition management research in almonds, so growers will have adequate information with which to make decisions that will optimize their yields without causing environmental degradation to surrounding communities.

The CVs provide no easily interpretable guidelines to almond growers regarding how to produce high-yielding trees. The challenge to UC researchers is to meet the growers' demands for yield-related plant nutrition information; this could potentially be accomplished by collecting a new type of data, re-interpreting the existing data, and/or performing focus group and/or survey efforts more frequently to consistently achieve a current perspective of whether they are meeting growers' informational needs.

The problems with CVs are both scientific (e.g., too much orchard variability, uncertainty as to how the CVs relate to new varietals) and practical (e.g., how the deficiency-related numbers translate into high yields, how a grower should use the mean values collected from tissue sampling to make decisions about the whole orchard). Since redesigning research projects to focus upon yields rather than deficiency would likely be expensive, it may be possible for UC researchers to creatively re-interpret the existing CVs to better meet growers' information needs. Perhaps, for instance, with understandings of the standard deviations of tissue samples within trees and across orchards, researchers will be able to identify optimal, rather than critical, values based on the existing data that was used to develop the CVs. These optimal values would meet growers' need for yield-related recommendations based on the mean values derived from collecting tissue samples on their orchards, although they still may not account for new varietals and changes in modern almond production.

A one-time, large-scale assessment of stakeholders' needs may be a suboptimal method with which to collect information to inform extension and research efforts because respondents may dramatically change their opinions of perceived needs within only a couple of years[10]. Researchers and extension agents may therefore benefit from frequent small-scale focus groups with stakeholders to ensure that extension and research projects continue to address the industry's changing needs. With the small amount of time and preparation necessary to involve stakeholders in continued research efforts, it may be possible to accurately and efficiently tailor agricultural projects over time, reassessing and redesigning research goals often enough to keep major holes from existing in the information they provide to growers. The results of the focus groups were useful both in their own right, allowing us to thoroughly understand stakeholders' motivations and concerns, and as a tool for informing a more detailed, quantitative research survey of a representative sample of growers.

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Greenhouse gas emissions from selected Austrian dairy production systems—model calculations considering the effects of land use change

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Abstract

The aim of this study was to analyze various Austrian dairy production systems (PS) concerning their greenhouse gas emissions (GHGE) in a life-cycle chain, including effects of land-use change (LUC). Models of eight PS that differ, on the one hand, in their regional location (alpine, uplands and lowlands) and, on the other hand, in their production method (conventional versus organic, including traditional and recently emerging pasture-based dairy farming) were designed.

In general, the GHGE-reducing effect of a higher milk yield per cow and year in conventional dairy farming cannot compensate for the advantages of organic dairy production which requires lower inputs. This is shown both for GHGE per kg of milk and GHGE per ha and year of farmland. Especially when (imported) concentrates were fed, which had been grown on former forests or grassland, e.g. soybean meal and rapeseed cake, GHGE of conventional dairy farming rose due to the effects of LUC.

GHGE per kg milk varied from 0.90 to 1.17 kg CO_2-eq for conventional PS, while organic PS on average emitted 11% less greenhouse gases (GHGs), the values ranging from 0.81 to 1.02 CO_2-eq per kg milk. Within each production method, PS with a higher milk output generally showed better results for GHGE per kg of milk produced than PS with a lower milk output. Nevertheless the latter showed clearly better results for GHGE per ha of land used, ranging from 5.2 to 7.6 Mg CO_2-eq per ha and year for conventional PS and from 4.2 to 6.2 Mg CO_2-eq per ha and year for organic PS. The results of this study emphasize the importance of a complete life-cycle assessment in the evaluation of impacts that dairy PS have on the climate.

Key words: dairy cow, milk, greenhouse gas emissions, land-use change, mitigation

Introduction

Agriculture, especially animal husbandry, causes considerable greenhouse gas emissions (GHGE). In the EU-15, agriculture accounted for approximately 10% of total GHGE in 2000[1]. On the one hand, cattle and other ruminants emit relatively large quantities of greenhouse gases (GHGs), particularly methane from enteric fermentation. On the other hand, a large percentage of the agriculturally utilized land in Austria is located in mountainous areas and uplands[2]. As in other regions that are dominated by grassland, cattle and other ruminants are an essential element of regional agricultural food production. Cessation of (livestock) farming in these regions would therefore have tremendous socio-economic and high ecological costs[2,3].

Grasslands, pasture and (tropical) forests are vegetations with a high environmental value, with high biodiversity and carbon storage potential[4,5]. Land-use change (LUC), especially in combination with forest clearing in the

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tropics, is assumed to cause up to one-quarter of anthropogenic CO_2-emissions[5]. However, the relative contribution of LUC to GHGE from traditional grassland-based dairy production through imported concentrates has not yet been studied[6]. Another source that is sometimes not considered in estimations of GHGE is the emissions occurring during the rearing period of heifers, on the one hand; on the other hand, beef from calves and cull cows are important by-products from dairy production which result in a relative reduction of GHGE accountable to milk production, but are nevertheless not always considered in respective calculations (e.g. Löthe et al.[7]).

Given the regional importance of agriculture in general, and especially of dairy production in alpine regions of Europe, local traditional production systems (PS) must be further developed, including a reduction of their GHGE. Nevertheless, for these PS mitigation options have not yet been extensively analyzed in the literature as most studies have covered more intensive lowland PS which were characterized by greater livestock density and higher quantities of purchased production factors, such as bought-in feed or chemicals (e.g. Thomassen et al.[8], Williams et al.[9] and Cederberg and Mattson[10]).

Therefore the goals of this study were to estimate the level of GHGE for selected milk PS in Austria, taking a great number of sources for GHGE into account, to analyze relevant influencing factors and to identify options for their reduction.

Material and Methods

Models for different PS were built, using MS Excel for calculation and taking into account emissions of methane (CH_4) and nitrous oxide (N_2O) from enteric fermentation and from manure management, as well as of CH_4, N_2O and carbon dioxide (CO_2) from soil, from the use of fuels and other energy sources and from production and application of mineral fertilizers and pesticides. Total emissions per cow and year, per kg milk and per ha of farmland used were calculated by adding up the emissions of CH_4, N_2O and CO_2 as CO_2-equivalents (CO_2-eq). Conversion factors used to calculate the global warming potential are 23 kg CO_2-eq for 1 kg methane and 296 kg CO_2-eq for 1 kg N_2O (100-year-horizon)[11].

Modeled dairy PS

Models for Austrian dairy PS were built on farm-level for alpine regions, uplands and lowlands, each one for organically and conventionally managed PS. PS a (alpine) represents a traditional alpine farm at more than 800 m asl and steeply sloping grassland. PS U (uplands) represents a dairy farm in a region of transition from alpine to lowlands with about 20% of arable land and 80% of permanent grassland, while PS L (lowlands) is located in the lowlands, farming on permanent grassland and arable land at a ratio of about 50 : 50. Generally, the intensity of production (i.e., among others, stocking rate and milk yield per cow) increases within these PS (PS A < PS U < PS L), while PS UP (uplands, pasture) represents a low-input, pasture-based production system with a relatively high stocking rate. Herein, the appendices '$_{org}$' and '$_{con}$' are used to further differentiate between organic and conventional PS, respectively. These PS may not necessarily represent the average Austrian dairy farm, but rather represent a wide spectrum of different conditions for dairy production. The great variability in farming conditions in Austrian dairy production are due to the geographic heterogeneity, to the originally small farm size and the different development during the past three decades. According to an analysis, which was based on a comprehensive Austrian agricultural statistical database (Invekos)[12], about 14% of Austrian dairy farms could be assigned to the PS A_{con}, A_{org}, UP_{con} and UP_{org} (between 4500 and 6000 kg milk quota per cow and year in an alpine or upland region), with a relatively high share (26%) of organic farms. Within these 14%, pasture-based PS contribute an estimated 15%. Although currently only relatively few farms exist which are strictly following a pasture-based low-input approach with the highest possible proportion of pasture (up to 60%; Table 1) and seasonal calving, this concept of dairy production is extensively discussed as a future strategy of milk production in permanent grassland regions[13]. PS UP_{con} and UP_{org} were defined to represent farms following such a strategy. PS U_{con} and U_{org} represent another 8% of Austrian dairy farms (i.e., with a share of grassland between 65 and 85%), with 16% of farms being organically managed. Furthermore, about 4% of Austrian dairy farms are represented by PS L_{con} and L_{org} with a milk quota of 6500–8000 kg milk per cow (among them about 9% of organic farms).

Due to differences in management (e.g., number of harvests, dietary proportion and type of bought-in and home-grown feed), milk yield and usage of fuel, mineral fertilizers and pesticides, among other factors, differ between the eight PS. Key characteristics for these PS are shown in Tables 1, 2 and 3.

Crop and grassland yields, feeding value. Values for crop yields were derived from Austrian statistical databases[14], differentiating between conventional and organic production. Yields for grassland were taken from Buchgraber and Gindl[15] and an agricultural national database[16] and were equal for conventional and organic production but were adjusted to the altitude. The main reasons for the assumption of equal forage yields were similar amounts of manure applied, lower gaseous N-losses in organic housing due to higher proportions of pasture and straw-based manure systems (20 and 30% gaseous N-losses from NH_3 and NO_x emissions for pasture and storage of solid manure, respectively, as compared to 40% N-losses for slurry systems; IPCC[17], Tables 10.22 and 11.3) and a higher share of legumes in organic grassland and hence higher biological N-fixation (e.g. Rahmann and Böhm[18]). Information on nutrient contents of crops and forage were derived from DLG feed tables[19], Buchgraber

Table 1. Emissions from manure management, direct and indirect soil emissions for the eight PS.

Trait	PS A_{con}	PS A_{org}	PS UP_{con}	PS UP_{org}	PS U_{con}	PS U_{org}	PS L_{con}	PS L_{org}
Percentage of manure excreted in straw-based systems (%)	43	40	24	24	60	51	60	51
Percentage of manure excreted in slurry-based systems (%)	29	26	16	16	40	33	40	33
Percentage of manure excreted on pasture (%)	28	34	60	60	0	16	0	16
N_2O—manure (kg cow^{-1} year^{-1})	1.2091	1.1280	0.6688	0.6791	1.8388	1.5220	1.9513	1.5688
CH_4—manure (kg cow^{-1} year^{-1})	25.49	23.30	15.67	15.43	37.13	30.32	39.26	31.26
CO_2-equivalents—manure (kg cow^{-1} year^{-1})	944.2	869.8	558.4	555.9	1398.3	1147.9	1480.6	1183.3
N_2O-emitting soil-N (kg cow^{-1} year^{-1})	114.5	110.6	70.1	70.1	112.5	102.4	95.3	98.8
Direct N_2O soil emissions (kg cow^{-1} year^{-1})	2.16	2.16	1.61	1.61	1.93	1.73	1.50	1.67
Indirect N_2O soil emissions from deposition and leaching (kg cow^{-1} year^{-1})	0.62	0.62	0.59	0.59	0.70	0.66	0.77	0.67

et al.[20] and Resch et al.[21]. The management and production factors for the different PS were defined based on Austrian agricultural statistical data[14,16,22,23], and are described in Tables 2 and 3.

Forage quality depended, among others, on altitude, cutting frequency and time of harvest or grazing, ranging from 5.35 to 6.15 MJ NE_L ('net energy lactation'[24,25]) per kg of dry matter (DM)[15,21].

Feeding regimen and milk yields. The relative proportion of pasture in the total forage was assumed to decrease from PS UP via PS A to PS U; in PS L_{con}, cows were not grazed anymore. The dietary percentage of hay also decreased in the same order, whereas the percentage of silage increased. In general, organic PS fed more hay and used more grazing than conventional PS, as it is shown in Table 2. In the most intensive PS L_{con}, about 40% of grass-clover silage were replaced by maize silage. Forage harvest-losses were related to the type of forage fed: pasture 25%, indoor grass feeding 5%, grass silage 20% and hay 30%, on a DM basis[16].

The annual average percentage of concentrate in the diets was assumed to be between 13% of total feed intake in PS UP (conventional and organic) and 24% in PS U_{con} and PS L_{con}. In the pasture-based PS UP_{con} and PS UP_{org}, the concentrate only consisted of grains and mineral premix. Organic concentrate consisted of barley, wheat, faba beans, peas and mineral premix for PS A_{org}, PS U_{org} and PS L_{org}. Conventional concentrate contained barley, wheat, corn, rapeseed cake, extracted soybean meal, faba beans and mineral premix for PS A_{con}, PS U_{con} and PS L_{con}. Forty-five percent of the rapeseed for oil milling (from which rapeseed cake originates as a by-product) was assumed to be imported from abroad (mainly from European countries such as Hungary and Slovakia), the rest was produced in Austria[26]. It was assumed that the production and extraction of soybeans took place mainly in South America and Germany, respectively[27]. While PS A and PS UP had to buy-in all the concentrates, PS U_{con}, PS U_{org}, PS L_{con} and PS L_{org} bought-in 56, 58, 53 and 24% of total concentrates, respectively.

Milk yields ranged from 5500 kg per lactation (organic and conventional PS UP and PS A) to 8000 kg per year (PS L_{con}), with an estimated average lifetime performance of 23,650 kg milk, as was recorded for Austria's main breed, Simmental[28].

Livestock density per hectare (stocking rate) was related to the PS as well as the feeding strategy and was between 1.0 and 1.5 livestock-units of dairy cows per hectare. Internal farmland was assumed to be between 0.67 and 1.0 ha per cow, but due to the demand on land for the production of bought-in feed, total farmland required ranged from 0.84 to 1.23 ha per cow (Table 3). Although cash crops may be produced, particularly in PS U and PS L, only land for cattle feed production was considered herein.

Sources of emissions

Enteric fermentation. Unlike CO_2 emissions from livestock, which are assumed to be zero due to photosynthesis of plants, emissions of CH_4 have to be considered according to IPCC[11]. CH_4 emissions from enteric fermentation were estimated using an equation established by Kirchgeßner et al.[29]:

$$CH_4 = 63 + 79\,CF + 10\,NfE + 26\,CP - 212\,EE,$$

where 'CH_4' describes the enteric methane emissions (in g), 'CF' is dietary crude fiber (in kg), 'NfE' is the dietary easily soluble carbohydrates (N-free extracts; in kg), 'CP' is the dietary crude protein (in kg) and 'EE' is the ether extracts (in kg). Table 4 shows some characteristic traits for the rations (Table 2) fed in the eight PS.

Table 2. Characteristics of feed production, feed quality and dietary composition for the eight PS.

Characteristic	PS A_{con}	PS A_{org}	PS UP_{con}	PS UP_{org}	PS U_{con}	PS U_{org}	PS L_{con}	PS L_{org}
Average number of cuts or frequency of pasturage for permanent grassland and clover ley (*n*)	2	2	4	4	3	3	4.5	4.5
Gross yields of permanent grassland/clover ley (Mg DM ha^{-1} $year^{-1}$)	6.0	6.0	9.0	9.0	8.0/8.5	8.0/8.5	10.0/11.0	10.0/10.5
Average energy density of forage[1] (MJ NE_L kg^{-1} DM)	5.40	5.35	5.90	5.90	5.60	5.60	6.15	5.80
Energy density of concentrate (MJ NE_L kg^{-1} DM)	8.05	8.05	8.00	8.00	8.05	8.05	8.05	8.05
Overall percentage (type[2]) of forage per kg diet-DM (%)	83 (grass silage, hay, pasture)	81 (hay, pasture, grass silage)	89 (pasture, hay, grass silage)	89 (pasture, hay, grass silage)	76 (grass-clover silage, pasture, hay, fresh grass)	83 (grass-clover silage, pasture, hay, fresh grass)	76 (grass-maize-clover silage)	81 (grass-clover silage, pasture, hay, fresh grass)
Overall percentage of concentrate per kg diet-DM (%)	17	19	11	11	24	17	24	19
Percentage of bought-in feed per cow (% DM)	17	19	11	11	14	10	13	5

[1] Including clover silage and maize silage in uplands and lowlands PS if existing.
[2] Feedstuffs ranked according to their dietary percentage.

Energy consumption. The energy directly used on farm for dairy production, as well as the fuels and electric energy that were consumed during the production of mineral fertilizers and pesticides, were considered herein. The greatest share of the electric energy needed on dairy farms is used to cool milk and to produce and supply (concentrate) feed. Therefore, the amount of energy used was related to the annual milk yield, also considering that more feed was required and that higher-mechanized (energy-consuming) housing systems coincided with higher milk yields. A value of 0.05 kWh per kg milk was assumed[30]. All calculations in this model were done per cow and did not account for differences in farm size. Emissions were estimated to be 0.453 kg CO_2-eq per kWh on average[31]. The amount of fuel used for cultivating the fields was estimated using standard values from a national database[32], resulting emissions were calculated according to Fehrenbach et al.[4]. Additionally, the energy needed in transporting externally produced feedstuffs was also taken into account according to Wilting et al.[33]. Mineral fertilizers and pesticides must not be used in the organic PS and were also not used on the grassland of the conventional PS, PS A_{con} and PS UP_{con}. However, a proportionate input of these factors was accounted for the concentrates imported into the conventional PS.

Emissions occurring during the production of mineral fertilizers and pesticides were derived from Patyk and Reinhardt[34] and Biskupek et al.[35]. Table 5 shows energy-related emission factors used herein and the references from which the data were derived. PS A_{con} is used as an example to demonstrate how the emissions attributed to these sources were calculated (Table 6).

Construction of machinery and buildings were not included as sources of emissions in the model calculations, as they were expected to be equal for all PS.

Manure management. The manure systems were assumed to represent the situation in Austria: 60.7 and 59.7% of the organic and conventional dairy cows, respectively, are housed in straw-based systems[23]. The remaining systems are slurry-based. Therefore, differences occur between the eight PS, according to the proportion of time spent on pasture; according to Amon et al.[22,23], the amount of manure per cow, its organic DM and nitrogen (N) contents, which are in turn related to milk yield and feed intake. Representative data were derived from Gruber and Steinwidder[36], the amounts of manure were calculated to be between 19.4 (for both PS A and PS UP) and 22.4 (for PS L_{con}) Mg per cow and year. The content of volatile solids excreted daily (DM) was calculated to be between 4.0 and 4.6 kg per cow, based on Schechtner[37]. The quantity of nitrogen excreted was estimated to vary from 86.2 to 100.6 kg per cow and year if a moderate N-content of feed is assumed[38]. Based on these values, the amounts of CH_4 and N_2O emitted were estimated according to IPCC[17] (tier 2; equations 10.23 and 10.25) and are given in Table 1, using methane conversion factors of 0.3, 0.04 and 0.015 for slurry, farmyard

Table 3. Key characteristics of the eight PS.

Characteristic	PS A_{con}	PS A_{org}	PS UP_{con}	PS UP_{org}	PS U_{con}	PS U_{org}	PS L_{con}	PS L_{org}
Regional location, production method	Alpine, conventional	Alpine, organic	Uplands pasture-based, conventional	Uplands pasture-based, organic	Uplands, conventional	Uplands, organic	Lowlands, conventional	Lowlands, organic
Stocking density (cow-LU ha^{-1})	1.0	1.0	1.4	1.4	1.2	1.1	1.5	1.2
Internal farmland required per cow[1] (ha)	1.0	1.0	0.71	0.71	0.83	0.91	0.67	0.83
Total farmland required per cow[2] (ha)	1.23	1.34	0.84	0.88	1.11	1.10	0.94	0.92
Permanent grassland, proportion of agricultural land (%)	100	100	100	100	80	80	50	56
Arable land, proportion of agricultural land (%)	0	0	0	0	20	20	50	44
Crop rotation on arable land and percentage of the crops (%)	–	–	–	–	Clover ley (20), wheat (25), barley (55)	Clover ley (25), barley (34), faba beans (25), wheat (16)	Clover ley (20), maize (35), barley (30), wheat (15)	Clover ley (25), barley (34), faba beans (25), wheat (16)
Annual milk yield per cow (kg)	5500	5500	5500	5500	7000	6500	8000	7000
Milk yield per ha of total farmland (kg)	4475	4103	6576	6223	6304	5913	8542	7606
Total farmland required per 1000 kg milk (ha)	0.223	0.244	0.152	0.161	0.159	0.169	0.117	0.131

[1] For the production of homegrown feedstuffs.
[2] For the production of homegrown plus bought-in feedstuffs.

Table 4. Nutrient intake and their relative dietary proportions for the eight PS.

Nutrient	PS A_{con}	PS A_{org}	PS UP_{con}	PS UP_{org}	PS U_{con}	PS U_{org}	PS L_{con}	PS L_{org}
CF (kg per day; [%])	3.43 [24]	3.47 [24]	3.44 [25]	3.44 [25]	3.27 [22]	3.51 [23]	2.98 [18]	3.21 [22]
NfE (kg per day; [%])	7.09 [50]	7.25 [51]	6.66 [48]	6.66 [48]	7.61 [50]	7.47 [49]	9.08 [56]	7.12 [50]
CP (kg per day; [%])	1.98 [14]	1.91 [13]	2.03 [15]	2.03 [15]	2.34 [15]	2.26 [15]	2.31 [14]	2.18 [15]
EE (kg per day; [%])	0.41 [3]	0.36 [3]	0.34 [2]	0.34 [2]	0.48 [3]	0.44 [3]	0.52 [3]	0.42 [3]
Ash (kg per day; [%])	1.34 [9]	1.29 [9]	1.41 [10]	1.41 [10]	1.45 [10]	1.52 [10]	1.25 [8]	1.41 [10]

CF, dietary crude fiber; NfE, dietary easily soluble carbohydrates; CP, dietary crude protein; EE, ether extracts.

Table 5. Overview on used emission factors.

Process	Unit	Emission factor	Reference
Fuels—emissions from supply chain and consumption	kg CO_2-eq l^{-1} diesel	3.2066	Fehrenbach et al.[4]
Electric energy—emissions from supply chain	kg CO_2-eq kWh^{-1}	0.453	Ecoinvent[31]
Production mineral fertilizer—nitrogen (N)	kg CO_2-eq kg^{-1} N-mineral	7.470	Patyk and Reinhardt[34]
Production mineral fertilizer—phosphorus (P_2O_5)	kg CO_2-eq kg^{-1} P_2O_5-mineral	1.176	Patyk and Reinhardt[34]
Production mineral fertilizer—potassium (K_2O)	kg CO_2-eq kg^{-1} K_2O-mineral	0.664	Patyk and Reinhardt[34]
Production pesticides	kg CO_2-eq kg^{-1} pesticide	5.369	Biskupek et al.[35]

manure and pasture, respectively. Emission factors used for calculation of N_2O were 0.02 and 0.001 for farmyard manure and slurry, respectively[17].

Soil N_2O. Direct N_2O emissions were calculated based on the amount of nitrogen introduced into the soil (IPCC-tier 2, equation 11.2)[17]. Amounts of N from mineral fertilizers, mineralization, manure and crop residues were multiplied by the default emission factors of 0.01 kg N_2O-N per kg of N applied; a factor of 0.02 kg N_2O-N was used for each kg of N excreted by cows on pasture. Indirect soil emissions from deposited nitrogen and leaching were estimated according to IPCC[17] (default values in Tables 10.22 and 11.3). In Table 1, amounts of N and related N_2O-emissions are shown for the different PS. N_2O emitted during cultivation of bought-in concentrates was included, because of its relevance for the N-balance of the total dairy supply chain. Due to a low demand on farmland and less grazing, soil N_2O-emissions per cow seem to be lower for more intensive PS. On the contrary, emissions from manure are higher for more intensive systems with little or no grazing (Table 1).

LUC and changes in soil organic carbon stocks. LUC for soybean production was calculated according to statistics on imports (98% of imported soybean meal originated from South America[27]) and based on estimates for the conversion of savannah-type vegetation into soybean fields[4]. The emissions from LUC, which may be even higher in the case of rainforest clearance, were calculated depending on loss of carbon from the soil and aboveground biomass and were allocated to soybean oil and extracted soybean meal based on their caloric values.

As supported by data from the European Environment Agency (EEA)[39], LUC from grassland to arable land could be neglected for Austria, but had to be considered for imports of rapeseed from Eastern and Central Europe. An equivalent of 53% of LUC-related GHGE was estimated for the CO_2-eq value of rapeseed cake by Fehrenbach et al.[4], which was used as feedstuff for dairy cattle, because 45% of the rapeseed further processed in Austria was imported mainly from Eastern and Central Europe in 2004[26]. Consequently, LUC-related GHGE of 5.41 and 0.40 kg CO_2-eq were calculated for soybean meal and rapeseed cake, respectively, in addition to emissions from cultivating, transport and processing.

CO_2 sequestrated into soil or released from soil organic carbon stocks was calculated according to Küstermann et al.[40] for Bavaria, Germany, where on-site conditions can be expected to be very similar to those in Austria. CO_2-emissions and -sequestration occur for conventionally ($+202\,kg\,ha^{-1}\,a^{-1}$) and organically managed soils ($-400\,kg\,ha^{-1}\,a^{-1}$), respectively, due to differences in crop rotation and manure management. An even higher sequestration rate of 575 kg CO_2 ha^{-1} a^{-1} was observed in a previous long-term study in Switzerland[41], where on-site conditions could also be expected to be similar to those in Austria.

It was estimated that 1 kg of conventional concentrate caused emissions of 0.05 kg CO_2-eq from soil organic carbon changes, based on $+202\,kg\,CO_2$-eq $ha^{-1}\,a^{-1}$ and an average grain yield of $4000\,kg\,ha^{-1}\,a^{-1}$. One kilogram of an organic concentrate was expected to be related to a sequestration of 0.111 kg CO_2-eq ($-400\,kg\,CO_2$-eq ha^{-1} a^{-1} and an average grain yield of $3600\,kg\,ha^{-1}\,a^{-1}$). Due to its long history of relatively constant management, it was assumed that Austrian alpine grassland is at an equilibrium state and that its soils did not emit or sequestrate further CO_2[42].

Rearing phase and beef as a by-product. The rearing phase of dairy cows prior to first calving has to be considered as an important source of GHGE, together with

Table 6. Consumption of energy and inputs per cow and year: PS A_{con} as an example.

Sources	Demand for fuels (litres)	Demand for additional mineral fertilizer[1] (kg $N/P_2O_5/K_2O$)	Demand for pesticides (kg)	Demand for electric energy (kWh)	Emissions from fuels (kg CO_2-eq)	Emissions from production of mineral fertilizer (kg CO_2-eq)	Emissions from production of pesticides (kg CO_2-eq)	Emissions from electric energy (kg CO_2-eq)
Reference	ÖKL[32], Wilting et al.[33]	BMLFUW[16]	Biskupek et al.[35]	Öhlinger et al.[30]	Fehrenbach et al.[4]	Patyk and Reinhardt[34]	Biskupek et al.[35]	Ecoinvent[31]
Forage (homegrown)	58.2	9.8/0/85.0	0	–	186.6	129.6	0	–
Concentrate (bought-in)	17.9	18.6/7.1/6.1	0.9	–	57.4	149.6	4.8	–
Transports	13.3	–	–	–	42.6	–	–	–
Housing	–	–	–	275	–	–	–	124.6

[1] Taking into account the amount of nutrients in the manure.

beef as the by-product from dairy production having a related mitigating effect for GHGE per kg of produced milk.

In the model calculations, the GHGE during the rearing phase were calculated for each PS based on the average emissions per MJ NE_L consumed during the rearing phase. In the same way, emissions for a growing–fattening heifer were calculated as a standard of comparison for each PS, based on the emissions per MJ NE_L. The mitigating effect of beef as a by-product from cull cows and newborn calves (50% bodyweight estimated as carcass) was calculated, using growing–fattening heifer as a model for beef from each PS. By considering all sources of GHGE except electric energy for cooling milk, 1 MJ NE_L was burdened with 0.15 kg CO_2-eq (PS L_{org}) to 0.19 kg (PS A_{con}). The total requirement for energy during a dairy cows' rearing phase was assumed to be about 31,000 MJ NE_L with an age at first calving of 28 months[28,43]. As a consequence, emissions during the rearing phase were calculated to vary from 4.7 for PS L_{org} to 5.9 Mg CO_2-eq per cow in PS A_{con}. Emissions during the growing–fattening of a heifer (about 20,000 MJ NE_L required for 600 kg final body weight) were estimated to vary from 3.0 to 3.8 Mg CO_2-eq per head; the mitigating effect of beef from slaughter cows and newborn calves was therefore calculated to be between 3.1 and 3.9 Mg CO_2-eq per cow.

Results and Discussion

GHGE from dairy PS

Emissions related to input factors and milk yield. Total emissions per cow (related to a lifetime milk yield of 23,650 kg) are presented in Table 7. The majority of GHGE evolved from enteric fermentation (40–62%), while the use of fuels and energy (in total 5–9%) as well as production of external inputs such as mineral fertilizers and pesticides (up to 7%) contributed relatively little. In Figure 1, GHGE from soil (N_2O), from fuels, fertilizers and pesticides used, were aggregated to GHGE accountable to forage and concentrate supply. As the same sources—except electric energy for cooling milk—contribute to emissions during the rearing period and to the mitigation of emissions indirectly caused by the by-product beef, total GHGE from enteric fermentation are actually higher than presented in Figure 1 and Table 7. For example, total GHGE from enteric fermentation are 53% of total emissions (i.e., 3326 kg CO_2-eq per year) as compared to 49% (i.e., 3100 kg CO_2-eq annually) which are attributed to one productive year of a dairy cow.

In previous calculations, which focused on the relation between GHGE and milk yield, emissions which originated from the rearing phase were not always taken into account (e.g., Löthe et al.[7]). Although milk yield remains to be an essential factor, the rearing phase is equally important, as a heifer needs nearly the same amount of energy for growth and maintenance as a cow during one lactation. Additionally, the production of beef as a by-product of dairy

Table 7. Emissions of GHGs (kg $CO_{2\ eq}$ cow $^{-1}$year $^{-1}$; [%]) from different sources for the eight PS, including the source 'rearing phase' and beef as a by-product.

Source of emission	PS A_{con}	PS A_{org}	PS UP_{con}	PS UP_{org}	PS U_{con}	PS U_{org}	PS L_{con}	PS L_{org}
Rearing phase—proportional emissions per lactation	1359 [21]	1167 [21]	1210 [21]	1198 [23]	1686 [23]	1314 [22]	1679 [23]	1359 [24]
Enteric fermentation	3100 [48]	3215 [57]	3209 [57]	3209 [62]	2995 [42]	3205 [54]	2841 [40]	2988 [52]
Manure	944 [15]	870 [16]	558 [10]	556 [11]	1398 [19]	1148 [19]	1481 [21]	1183 [21]
Forage—fuels	187 [3]	179 [3]	133 [2]	133 [3]	189 [3]	199 [3]	165 [2]	193 [3]
Forage—inputs	130 [2]	0 [0]	264 [5]	0 [0]	167 [2]	0 [0]	140 [2]	0 [0]
Forage—direct N_2O	547 [8]	561 [10]	564 [10]	564 [11]	409 [6]	426 [7]	223 [3]	281 [5]
Concentrates—fuels	100 [2]	106 [2]	37 [1]	58 [1]	161 [2]	125 [2]	226 [3]	177 [3]
Concentrates—inputs	154 [2]	0 [0]	104 [2]	0 [0]	125 [2]	0 [0]	166 [2]	0 [0]
Concentrates—direct N_2O	86 [1]	78 [1]	58 [1]	58 [1]	150 [2]	122 [2]	257 [4]	182 [3]
Indirect soil emissions—N_2O	183 [3]	179 [3]	176 [3]	176 [3]	206 [3]	196 [3]	228 [3]	199 [3]
Changes in soil organic carbon	48 [1]	−113 [−2]	37 [1]	−81 [−2]	73 [1]	−109 [−2]	77 [1]	−121 [−2]
Production of energy in housing	125 [2]	125 [2]	125 [2]	125 [2]	159 [2]	147 [2]	181 [3]	159 [3]
By-product beef—proportional emissions per lactation	−895 [−14]	−772 [−14]	−801 [−14]	−793 [−15]	−1116 [−16]	−870 [−15]	−1112 [−15]	−899 [−16]
LUC	389 [6]	0 [0]	0 [0]	0 [0]	589 [8]	0 [0]	628 [9]	0 [0]
Total GHGE	6452 [100]	5594 [100]	5675 [100]	5203 [100]	7190 [100]	5902 [100]	7181 [100]	5699 [100]
Total GHGE related to milk yield (kg $CO_{2\ eq}$ kg^{-1} milk)	1.173	1.017	1.032	0.946	1.027	0.908	0.898	0.814
Total GHGE related to total farmland (kg $CO_{2\ eq}$ ha^{-1})	5246	4175	6756	5913	6477	5365	7639	6195

production, lifetime performance and the number of lactations that a cow lasts, are important factors as well. Following Fürst[44], conventional and organic Austrian dairy cows are expected to produce about the same amount of milk in their lifetime, but with the latter being different.

Generally, PS with a higher output of milk showed higher GHGE per cow and year but were superior over PS with a lower output if emissions were expressed per kg of milk. GHGE per kg of conventional and organic milk were between 0.90 and 1.17 kg CO_2-eq per kg of milk and between 0.81 and 1.02 kg CO_2-eq per kg of milk, respectively (Table 7, Fig. 1). These numbers illustrate that differences may be smaller between production methods (i.e. conventional versus organic) than between regions: on average, organic PS showed about 11% lower GHGE per kg milk than comparable conventional PS, while the relative difference between the lowest emissions from the PS L and the highest emissions from the PS A amounted to 22%. Generally, the higher the dietary energy and nutrient density, the higher the milk yield, which results in lower GHGE per kg of milk due to reduced enteric fermentation and performance-related degression.

As the nutritional value of forages and concentrates is routinely characterized by proximate analysis in Austria, enteric fermentation was calculated according to the regression equation published by Kirchgeßner et al.[29]. In order to check these estimates, a regression equation derived by Hindrichsen et al.[45] was used. It was found that estimates resulting from the equation by Kirchgeßner et al. were on average 8% higher than those resulting from the equation of Hindrichsen et al., with the difference being greater for rations that are rich in crude fiber and being lower for rations rich in soluble carbohydrates.

The role of LUC. Another highly relevant source of GHGE has to be taken into account whenever conventional PS utilize soybean meal originating from South America: the production of soybeans is linked to an LUC from former savannah-type vegetation into arable land. In contrast to most previous calculations of GHGE and life-cycle assessments which did not incorporate LUC in their calculations (e.g., Lehuger et al.[46]), LUC was taken into account in this study (Table 7, Figs. 1 and 2) due to its high relevance on the global scale[4,5,11]. Estimates for GHGE from LUC vary considerably, e.g., about 5 kg CO_2-eq per kg of Argentinean soybean meal[47] as compared to more than 10 kg CO_2-eq per kg of Brazilian soybean meal. The latter occurs if soybean is cultivated on deforested land (calculated from Renewable Fuels Agency[48]). Herein, a change from extensive grassland (savannah) to arable land was assumed[4], but without deforestation. Since 2000, the area for soybean cultivation expanded predominantly on deforested land[49] and therefore emissions from LUC may actually be even higher than calculated by both Fehrenbach et al.[4] and within this study. Nevertheless, even with relatively low estimates for GHGE from LUC, emissions per kg milk will be lower for PS which do not import soybean meal into their

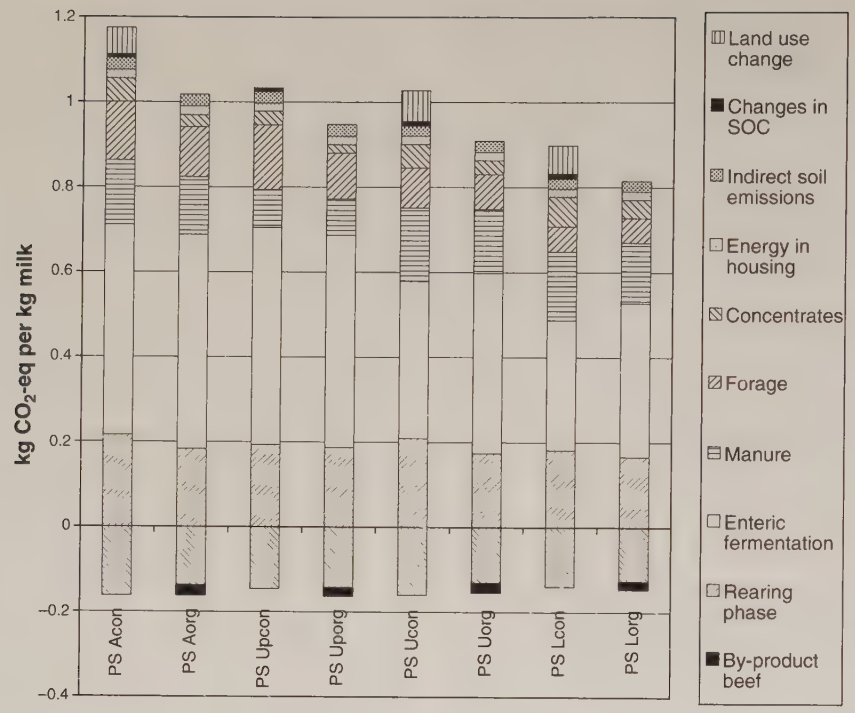

Figure 1. GHGE (kg CO_2-eq) per kg milk for the eight PS.

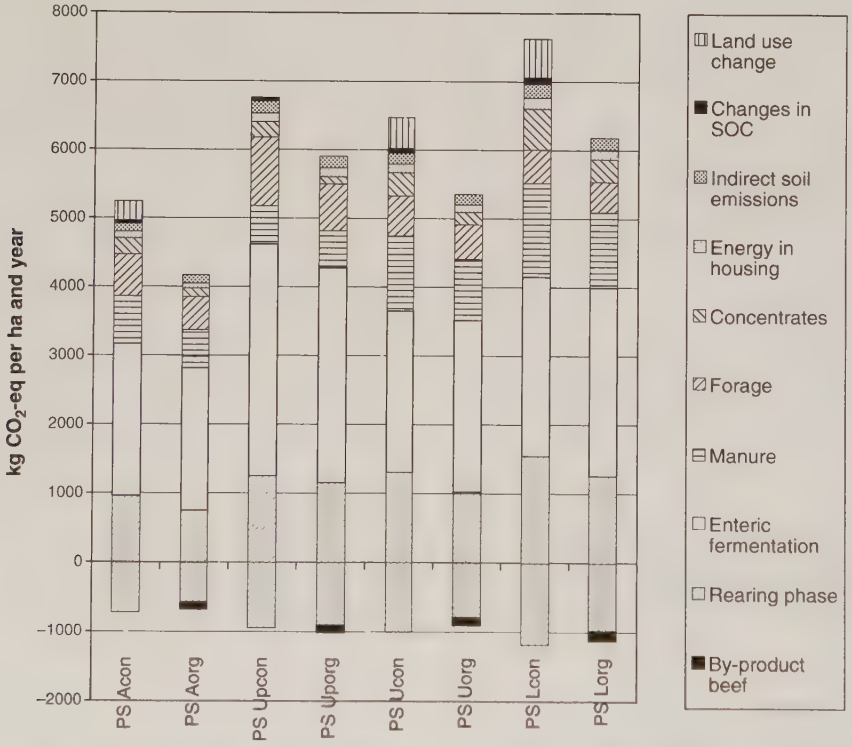

Figure 2. GHGE (Mg CO_2-eq) per ha and year of total farmland for the eight PS, including the source, rearing phase, and beef as a by-product.

system, but utilize homegrown or locally produced protein sources such as grain legumes or oilseed cakes. This contributes to the average difference in GHGE of 11% between conventional and organic PS studied herein. About 8% of total GHGE in conventional farming (average over all conventional PS excluding PS UP_{con}) result from LUC, mainly (93%) for extracted soybean meal originating from South America.

Emissions and regional location of dairy production. The difference in GHGE between alpine and lowlands PS with both conventional and organic management is mainly due to higher milk yields in the lowlands as well as a decreased enteric fermentation as a consequence of increased dietary energy density. Pasture-based PS (UP) emit relatively low amounts of GHGE per kg milk, despite their comparably low milk yield of 5500 kg per cow and year. This is caused by several factors, including reduced emissions from manure in housing (with cows being on pasture for 60% of the time) and the use of low amounts of concentrates. On the contrary, GHGE from enteric fermentation are slightly higher as compared to PS that use less hay but more silage. Pasture-based systems also have higher GHGE from forage because of a doubled rate of N_2O from N excreted during grazing[17], as compared to N spread as manure. Both the conventional and organic PS UP show a high productivity per ha of farmland required and low GHGE, which are similar to those of PS U.

Only very few studies are available about GHGE from dairy PS located in alpine or nearby regions (e.g. Weiske et al.[50] and Olesen et al.[51]). In contrast to the results presented herein, Weiske et al., using a model based on Olesen et al., reported generally higher GHGE per kg milk of between 1.2 and 2.0 kg CO_2-eq although LUC was not included in their calculations. The differences may be due to the lower milk yield and a lack of differentiation between organic and conventional PS in milk yield as assumed by Weiske et al., a greater number of input factors considered (e.g., the production of mineral premix and seeds), but also disregarding the emission-mitigating effects of by-products.

Great differences occur between PS when GHGE are related to the area of farmland used (Fig. 2). From this perspective, low-input systems show clearly better results. Organic PS need more area per cow due to lower yields especially from arable land, and at the same time show less GHGE per cow. As presented in Figure 2, GHGE per hectare of total farmland vary from 5.2 to 7.6 Mg CO_2-eq and from 4.2 to 6.2 Mg CO_2-eq for conventional and organic PS, respectively. Olesen et al.[51] reported comparable results of 8.7 Mg CO_2-eq for conventional PS and 6.0 Mg CO_2-eq for organic PS calculated according to an IPCC tier 2 methodology[52].

Mitigation options for dairy PS

A number of possibilities exist to mitigate GHGE, some concerning the animals, e.g., their genetics for milk yield, but most address management practices. Because of the complex interactions between the various elements of dairy PS and the factors influencing them, any measures intended to reduce the GHGE must be thoroughly examined, as they may exert effects that eventually counteract the intended mitigation.

Feed quality and LUC. One of the most effective strategies to reduce emissions is to increase the energy density of the diet, which usually results in the suggestion to increase the proportion of dietary concentrates. On the one hand, this will lead to a significant decrease of GHGE from enteric fermentation (e.g., −6.5% for PS U_{con} as compared to PS U_{org} if equal milk yields and energy intakes are assumed). On the other hand, increased GHGE from soils and from the use of fertilizers coincide with this mitigating effect and partially counteract it. If an increased use of concentrates is accompanied by LUC (i.e., by converting grassland or pasture into arable land), the mitigating effect of using concentrates turns into an aggravating effect, as shown herein. Another limitation of this practice is the growing probability for digestive and other health disorders associated with increased levels of concentrates in the diet of dairy cows[53,54]. Due to the core role of forages in grassland-based PS (herein, diets were assumed to consist of 76–87% of forage), improving the nutrient density of forage should be prioritized in order to reduce GHGE from enteric fermentation. The greatest effect may be achieved by reducing crude fiber in forage by earlier harvesting (or grazing), but this option is also limited for reasons of grassland ecology[55,56]. According to the calculations conducted within this study, an increase of 0.1 MJ NE_L per kg forage DM will lead to a reduction of total GHGE of about 1.5%.

Lifetime performance. Reducing age at first calving and thereby the rearing phase as well as decreasing the number of lactations in which a constant lifetime performance is yielded would result in a reduced demand for dietary energy and therefore in a reduction of GHGE. On the contrary, a decreased age at first calving and a continuing increase in milk yield per lactation may negatively affect lifetime performance, the number of lactations and the number of offspring per cow[57]. However, an improved lifetime performance (together with a constant or even increasing number of lactations) may be an effective way to decrease GHGE, because emissions from the rearing period will be distributed over a greater amount of milk: GHGE per kg of milk would be reduced by 1.4% on average if lifetime performance was increased by 5000 kg (i.e., from a current value of 23,650 to 28,650 kg for Austria).

Manure management. Furthermore, great potential for reduction of GHGE arises from changes in manure management. The PS in this study were assumed to represent the Austrian situation, where 59.7 and 60.7% of the dairy cows were kept in straw-based systems on conventional and organic farms, respectively[23]. All other cows were kept in systems with slurry production. GHGE from cows' excreta were lower for housing systems with straw litter than for slurry-based systems. A change toward straw-based systems would therefore be desirable because of reduced GHGE and also of a potentially beneficial effect on animal welfare[58]. GHGE per kg milk may be mitigated by 0.9% if a further 10% of dairy barns are

changed from slurry- to straw-based systems. However, this is not reflected by the current trend in Austria, where most of the newly built housing systems are slurry based[22]. Moreover, the separation of slurry into solid and liquid phases, as well as an aeration of slurry and composting of farmyard manure would contribute to a mitigation of GHGE, but may lead to increased ammonia emissions[59]. Over all PS covered herein, slurry separation and slurry aeration would reduce total GHGE by 1.8% on average.

When calculating GHGE from manure falling on pasture, only CH_4, but not N_2O, was taken into account, as the latter was already included in the emissions from soil[17]. Overall, pasture-based systems can be considered not only as animal friendly but also as favorable from the point of view of GHGE, as they are emitting less GHG than any other housing systems. On average, cows that spend 10% of their annual time budget on pasture emit 2.4% less GHG as compared to cows that are confined all year round.

Another very substantial reduction potential arises from anaerobic fermentation of manure for biogas production[60], whereby GHGE per kg milk can be decreased by about 5%. Additionally to this direct reduction, the substitution of fossil fuels by biogas could contribute to a further decrease, as 1 Mg of cattle manure can be transformed into 32 kWh of electric energy in a biogas plant[61]. For the PS covered in this study, this would lead to a reduction of total GHGE per kg milk by 7%. Depending on the degree of utilization of the heat that emerges in a biogas plant and the potential substitution of fossil energy for heating, a further potential reduction of GHGE arises.

Utilization of oil seeds for feed and biofuels. The utilization of by-products from the production of biofuels in livestock nutrition is frequently advocated as a contribution to improved sustainability of agricultural production (e.g., UN-Energy[62]). Nevertheless, certain energy crops, such as rapeseed, are frequently reported to cause higher emissions of N_2O than assumed by IPCC and as used in this study and in most previous calculations and reports (e.g., The Royal Society[63])[64]. According to Crutzen et al.[64], the N_2O-emissions from rapeseed are 3–5 times higher than reflected by IPCC[17] default values and current state of life cycle analysis. Assuming five times higher N_2O-emissions for rapeseed, total GHGE from milk would increase by an average of about 2%—or even more in the case of LUC—for the conventional PS.

Reducing energy required for mineral fertilizers and fuels. Besides the production of renewable energy from biogas (as stated in 'Manure management' section), the application of fertilizers and related management measures deserve specific attention concerning their contribution to GHGE. Because emissions from soil increase when the available amount of N in the soil increases[17], the quantity of nitrogen applied must be thoroughly adjusted to the requirements of plants. Furthermore, mineral fertilizers that need large amounts of (fossil) energy during production and transport should be substituted as much as possible by livestock manure. On a long-term basis, housing and manure management systems should therefore be designed in a way that the emissions of nitrogen are kept as low as possible. According to IPCC[17] and calculations herein, pasture can be expected to protect nitrogen very well against emission processes. The use of fossil energy can also be reduced if feeding is generally based on the utilization of pastures and the avoidance of feedstuffs transported over long distances. As an example, the transport of soybeans from Brazil and of extracted soybean meal to be used in PS L_{con} requires 12.3 liters of diesel per cow and year (0.57% of total GHGE).

Conclusions

From the results presented herein and from information provided in the literature, it is concluded that organic milk PS are superior over conventional systems in terms of GHGE both per ha of farmland and per kg of milk. A relevant factor for these differences is LUC as a source for emissions, especially associated with soybean production in South America. For the systems considered in this study, the difference in GHGE per kg of milk between conventional and organic systems depends on the site-specific conditions for agricultural production: the higher the potential milk output per cow, the lower the differences that can be expected.

Regardless of the actual production system, the greatest proportion of GHGE originates from enteric fermentation. Although this inevitable source of emissions can be influenced quantitatively, clear limits exist for the degree of reduction that can be reached. Apart from enteric fermentation, manure management and forage supply also contribute substantially to GHGE. Consequently, dairy PS in which the focus lies on optimum forage quality, a high proportion of pasturage and additional fermentation of the manure in biogas plants will produce relatively low GHGE.

Despite the focus of this paper, the question of sustainable food production should not be restricted to factors that are currently discussed in connection with climate change. However, organic and low-input PS undoubtedly possess a number of strong points with regard to ecological and ethical aspects of sustainability.

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ERRATUM

Greenhouse gas emissions from selected Austrian dairy production systems—model calculations considering the effects of land use change—ERRATUM

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In Figures 1 and 2, a printing error was made concerning the crosshatching for the bar "By-product beef" in the symbol key. The correct crosshatching for "By-product beef" is ▧.

Reference

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Local versus organic: A turn in consumer preferences and willingness-to-pay

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Abstract

Demand for local food in the US has significantly increased over the past decade. In an attempt to understand the drivers of this demand and how they have changed over time, we investigate the literature on organic and local foods over the past few decades. We focus our review on studies that allow comparison of characteristics now associated with both local and organic food. We summarize the major findings of these studies and their implications for understanding drivers of local food demand. Prior to the late 1990s, most studies failed to consider factors now associated with local food, and the few that included these factors found very little support for them. In many cases, the lines between local and organic were blurred. Coincident with the development of federal organic food standards, studies began to find comparatively more support for local food as distinct and separate from organic food. Our review uncovers a distinct turn in the demand for local and organic food. Before the federal organic standards, organic food was linked to small farms, animal welfare, deep sustainability, community support and many other factors that are not associated with most organic foods today. Based on our review, we argue that demand for local food arose largely in response to corporate co-optation of the organic food market and the arrival of 'organic lite'. This important shift in consumer preferences away from organic and toward local food has broad implications for the environment and society. If these patterns of consumer preferences prove to be sustainable, producers, activists and others should be aware of the implications that these trends have for the food system at large.

Key words: local food, preferences, willingness to pay, organic lite

Introduction

Extant research has addressed drivers of local and organic food demand, willingness to pay (WTP), consumer perceptions and other important dimensions of alternative foods. Particularly important to alternative food system producers and advocates is the nature of these rapidly changing views, which have consequences in the broader context of the food system.

What began as an alternative to industrial agriculture and conventional food has developed into a local food movement. This is evidenced by popular books such as *The Omnivore's Dilemma*[1], and *Animal, Vegetable, Miracle*[2], and documentary films such as *Food, Inc.* and *King Corn*. In 2007, the word 'locavore' (a person with an eating preference for local foods) was added to the New Oxford English Dictionary[3]. The popularity of local food has grown in response. According to the USDA's Agricultural Marketing Service, in 1994 there were 1755 registered farmers' markets, which grew to 4685 in 2008[4]. Total value of sales at farmers' markets in 2007 was $1.2 billion, up from $404 million in 1992[5]. Community supported agriculture programs (CSAs) have also seen significant growth in the past decade. The number of CSAs in the US has increased from just 50 in 1985 to about 2500 in 2008[6,7]. Other outlets for local food sales such as roadside stands, small and independent local grocers and direct sales to local restaurants have also seen significant growth[8].

The value of local food in the US market jumped from an estimated $4 billion in 2002 to about $5 billion in 2007, and is expected to increase to $7 billion by 2012[9]. This has piqued the interest of many groups in local food. For example, retail and processing giants such as Wal-Mart and Frito-Lay offer local ingredients, and new retailers such as New Seasons Market are finding success by focusing in part on food miles[10]. Much of this change is in response to studies that indicate a high WTP for local food.

We know that organic foods benefit from a concrete definition and a certified labeling program, but local food is a more abstract concept, with definitions often varying by

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consumer perceptions. Many define local to be within a certain geographical distance, such as 100 miles, while some define local to mean some political boundary, such as a state border. Others point to a definition more rooted in ethics, community and other factors not directly corresponding to food miles[11]. While there is no firm or standard definition for local, interest in local foods is high among consumers, producers and retailers.

What is unclear from previous work is (1) the linkage between the federal organic standards and the turn in demand for local food, and (2) the implications that this turn may have for the food system going forward. We describe the development of the local food movement and the change in consumer preferences concerning organic and local food characteristics, both pre- and post-USDA organic standards implementation. As large agribusinesses seek to capitalize on changes in consumer preferences, farmers' markets, CSAs and other direct and niche local food markets may be vulnerable to corporate co-optation[10]. This has serious implications for small farmers, consumers and many other stakeholders. In this context, our review provides some insight into the marketing potential of 'local' and the potential for its co-optation by industrial agriculture into 'local lite'.

Our work extends the literature by specifically examining the studies that allow a direct comparison between characteristics now associated with local or organic foods. Our analysis indicates a turn in demand from organic to local that is coincident with the development of the federal organic standards. We discuss the implications of this on the potential corporate involvement in providing local food.

Industrial Agriculture and the Federal Organic Rule

It took 12 years for the USDA to adopt national standards for the production, processing and marketing of organically labeled food under the Organic Food Production Act of 1990[12]. The USDA officially adopted the federal organic standards in October 2002 once it was satisfied that organic food would not 'disparage the rest of the food supply'[13]. The Organic Rule defines the minimum production, processing and input standards (National List of Allowed Substances) that must be met to use the organic label. The standards (1) apply to both domestically produced and imported organic products; (2) contain a list of allowed synthetic and prohibited nonsynthetic substances and a list of specific exceptions to the organic label requirement; (3) employ distinct guidelines for organic crops standards and organic livestock; (4) strictly define the handling and processing of organic products; and (5) include the USDA organic seal and a four-tier organic labeling scheme: '100% organic', 'organic', 'made with organic ingredients' and 'product contains some organic ingredients'.

Substantial price premiums coupled with public demand drew large agribusinesses into the organic foods market[13,14]. In 2006, sales of organic products reached $16.7 billion (3% of the $596 billion US food market), representing an annual growth rate of 20.9%[15]. Just 5 years earlier, sales of organic food products were $7.4 billion. Organic food now has more market share and a broader reach, but it is fundamentally different in character than when it started. Between 1990 and 2002, corporate agribusinesses took advantage of the USDA's formal rulemaking processes that disfavored the more ideological aspects of the organic movement[16], and lobbied to allow genetically modified ingredients, irradiation, chemically raised meats and several previously prohibited substances[17]. By 2002, when the USDA adopted its Organic Rule, 'organic' was federally defined as an input-driven technical process rather than a concept based in sustainability; food could still be labeled organic if it was made by General Mills corporation, produced in China using forced labor, and sold only through Wal-Mart[18].

Organic foods fundamentally changed with the development of the federal standards. Effective marketing campaigns co-opted the central themes of the organic movement to increase market share, while the products were largely grown on farms that either abandoned the sustainable agronomic practices associated with organic agriculture or were recruited from the ranks of conventional agriculture[19]. This resulted in the conventionalization (taking on the characteristics of conventional agriculture) and bifurcation (dual structure of very large and very small producers) of organic agriculture[20]. The entry of large corporations, such as Danone and General Mills[21], and the consolidation of food retail outlets, such as Whole Foods and Wild Oats[22], effectively cut out small farmers from the benefits of the boom in demand for organic foods. Production of organic food was forced toward large-scale, least-cost, input-oriented standards[19], and smaller competitors and those not adopting a least-cost production model were largely marginalized[13]. Today, the organic market essentially functions as an oligopsony, with a small number of very powerful wholesaler/retailer 'organic giants' who limit farmer income; about 80% of the organic food market is handled by just two national distributors[21,23].

Local as Response to 'Organic Lite'

Many argue that organic food now suffers from the same problems that initially spurred the organic movement (see review by Feenstra[24]). Early advocates of organic food focused on concepts now associated with local food. These included a discussion by Hightower[25,26] of the corporate control of US agriculture, including its impacts on small farmers, farm workers, consumers and food quality; Berry's[27] description of the associated loss of community and culture; Gussow's[28,29] essays on concerns over food, nutrition and the environment; and more recently,

Table 1. Comparison of local, organic and deep organic foods[1].

Attributes	Local	Deep organic	Organic lite
Production methods, inputs	Any	Pesticide and GMO-free, IPM; often very eco-friendly, sustainable and biodynamic	Pesticide- and GMO-free
Types of products	Wider variety, heritage varieties, seasonally available multi-purpose livestock and poultry	Wider variety, heritage varieties, seasonally available multi-purpose livestock and poultry	Traditional
Location	Local, but loosely defined	Local	Anywhere (even China)
Certification	No formal standards	None	Strict standards
Labeling	Federal—none State—often yes	None	USDA organic labels
Relationship to consumer	Close	Close	Distant
Market concentration	None	None	Dominated by large producers and retailers
Scale of production	Small	Small	Typically very large
Length of food chain	Short—direct to consumer	Short—direct to consumer	Long—involves wholesalers, shippers, storage, etc.
Impact on environment	Same as industrial agriculture, but smaller scale impacts	Eco-friendly	Less pollution from pesticides, but otherwise same as other industrial farms
Impact on local community, farm workers, animal welfare, etc.	Positive	Very positive	Same as industrial agriculture

[1] Adapted from a review of the literature.
GMO, genetically modified organism; IPM, integrated pest management.

Kneen's[30] review of the social and ecological costs of the global industrial food system that stood in opposition to sustainability, food justice and community.

Organic food lost its essential nature as an alternative to industrial agriculture[31]. While the number of certified organic acres in the US nearly quadrupled from 1995 to 2005, the average size of certified organic farms more than doubled from 189 acres to 477 acres[32]. Some argue that many organic products achieve only the minimum standards such as pesticide- or GM-free content: 'organic lite'. Today, every state in the US reports having at least one organic certified farm, but just 16% of organic foods are sold through direct marketing channels, such as farmers' markets, CSAs, cooperatives, etc[33]. The term 'organic lite' draws stark contrast with 'deep organic', which is identified with smaller scale, eco-friendly farming systems[19], or a dualism between shallow/corporate and deep/agri-ecological organic[34].

Critics view organic lite as 'dangerously incomplete' because it lacks a social vision[35]. Dimensions such as community food security, farm-worker welfare, animal welfare, land stewardship, resource conservation, preservation of heritage breeds and sustainability are no longer strongly associated with organic foods[14] both in the US[19] and abroad (e.g., Ireland[16], Great Britain[36,37], Australia and New Zealand[38,39]). Many in the organic movement were deeply disappointed by the effects of the Organic Food Production Act: 'When we said organic we meant local. We meant healthful. We meant being true to the ecologies of the region. We meant mutually respectful growers and eaters. We meant social justice and community. In other words, industrial organic farming isn't really organic'[17]; organic is 'more about fairness and respect than it is about parts-per-billion of pesticide residues'[18].

Many consumers have turned to local foods as a more holistic and authentic substitute for organic. For some, food miles rather than organic labels are the representation of sustainability[40], and organic movement supporters are now looking to local as the solution to industrialized organic foods: 'as organic consumers, the first and foremost action we can take is a commitment to buy food produced as locally as possible'[41]. For these consumers, local appears to be adequately defensible from 'opportunistic corporate greening'[42] in marketing campaigns and takeover by industrial agriculture. The concept of local food presents a difficult problem for the large agribusinesses that now dominate the market for organic foods. 'Foodsheds'[43] and 'civic agriculture'[44] leave no room for industrial farming, organic or otherwise. Both concepts stress the importance of eating close to home to reduce environmental and social externalities[43] and rebuild communities[44]. Local food has also gained interest from small organic farmers that reject certification and prefer to rely on a trust relationship with their consumer[20]. See Table 1 for a comparison of local, organic and deep organic.

The Turn in Preferences for Local and Organic Food

We review the literature on consumers' perceptions and WTP for local and organic food characteristics. Comparisons between local and organic food can be made both by summarizing generic findings for organic and local separately (sort of a meta-analysis), and by examining studies that explicitly include characteristics of both local and organic within the same study. We organize the studies into two groups: (1) where characteristics associated with local food are viewed as less important than those traditionally associated with organic foods today; and (2) where local is considered more important than organic. We summarize the key studies below, and highlight a turn in the demand for local food characteristics.

Local LESS important than organic

Numerous studies focus on factors influencing demand for *organic* food and consumer perceptions of various food characteristics that include consumer health, environmental impacts, etc. Very few of these studies also include characteristics associated with *local* food.

Most of the studies regarding organic consumers' motivations focus on perceptions of organic, attitudes and factors that influence purchases[45] or WTP for foods with varying levels of pesticide contamination, labeling, etc. (see review by Thompson[46]). These studies typically conclude that organic consumers are motivated by concerns for the environment, consumer health and safety, and product attributes such as price, taste, appearance and freshness (e.g., Tregear et al.[47], Browne et al.[48]).

Older studies of organic food found clear evidence of stronger preferences and/or WTP for characteristics associated more with organic food than for local food. Some of these studies involved consumers ranking food attributes. Studies implemented prior to the late 1990s found very strong support for factors such as protection of the environment, consumer health and conservation of resources, but weak support for supporting local communities, protection of farm workers and ecologically driven concepts such as preservation of nature–farm balance (e.g., Hawkes and Stiles[49], Sachs et al.[50], Goldman and Clancy[51], Sparling et al.[52] and Govindasamy et al.[53]). For example, Sparling et al.[52] found over three times more respondents indicating that concern for the environment was a major reason for purchasing organic than any factor now linked to local food (i.e., protection of farm workers). Likewise, Goldman and Clancy[51] found that concern for different aspects of the environment accounted for the top three of the seven ranked reasons for buying organic produce, while protecting farm workers ranked fourth and preserving a balance of nature only ranked sixth. Govindasamy et al.[53] is the most recent study we uncovered that found very little support for local over organic food characteristics. Their mail survey asked consumers in New Jersey to rank 19 product characteristics in order of importance. Traditional product characteristics (i.e., freshness, taste/flavor and cleanliness) were rated highest and health value and absence of pesticides were next highest, while locally grown and country of origin were rated among the least important. Unfortunately, their survey did not examine other dimensions of local food (e.g., supporting small farmers).

A handful of studies from this period focus on food origin, but neglect a comparison with organic foods. Two of these studies found that consumers were much more interested in product quality, price, appearance and other traditional demand factors than product origin[54,55]. For example, Kezis et al.[54] surveyed consumers by mail in Maine, Delaware and West Virginia, and found that produce origin was much less important than quality, appearance, price, convenience and variety. Lockeretz[55] conducted intercept surveys at supermarkets, farmers' markets and agricultural fairs in Massachusetts, and found that only 14% at farmers' markets or fairs indicated support for local farms as a reason for shopping there. Instead, they valued freshness, convenience, prices and selection. The other two studies examined price premiums and found very little support for local food[56,57]. Eastwood et al.[56] conducted consumer interviews in Tennessee, and found a very weak WTP premium for local tomatoes and peaches, but negative WTP for other local goods. They concluded that local produce should be priced below comparable out-of-state products. Bruhn et al.[57] conducted intercept surveys at supermarkets, and found that 78% of respondents considered locally grown to be an unimportant characteristic; only 13% expected to pay a price premium for locally grown foods. Clearly, the locality of food sources was not considered a priority for most consumers during this period.

Local MORE important than organic

The turn from organic to local foods became apparent in studies conducted around the late 1990s. Both in the US and abroad, researchers began to note odd results in organic food studies. For example, a study of British consumers found that concern for the environment did not help differentiate organic produce buyers from nonbuyers[47], and only 9% of respondents indicated that concern for the environment was their primary reason for buying organic. Likewise, there was evidence that certified organic was losing its credibility and consumer support[58]. Underhill and Figueroa[58] surveyed residents of eight northeast US states to determine the relative impact of organic and certified organic on WTP. They found a slight preference for organic over certified organic (about 5% higher predicted probability of buying organic than certified organic) that could be interpreted as a preference for small farms. Also, several studies found that protection of self (consumer's health) was not the primary motivation for purchasing organic (e.g., Gallons et al.[59]).

The tipping point occurred in the late 1990s when studies began to find that consumers place a greater importance on

purchasing local rather than organic foods, and they perceive that local foods are better for society (e.g., Gallons et al.[59], Zumwalt[60]). For example, Wolf[61] found that consumers in California rate locally grown as somewhat to very desirable, a much higher rating than is given to grown organically. A later study by Wolf et al.[62] reported that California residents indicate locally grown to be a moderately important factor for shopping at farmers' markets, while organically grown is only a slightly desirable factor; shoppers also perceived local food as being fresher, better quality and more affordable. Gallons et al.[59] found that locally grown is a very important (49%) or somewhat important (31.5%) reason for Delaware residents to shop at direct markets (e.g., farmers' markets). Fewer consumers indicated that organically grown was a very important (15.8%) or somewhat important (19.9%) reason.

Studies also began to find that these preferences for local foods translated into high WTP. Kezis et al.[63] interviewed consumers at Maine farmers' markets and found both a high relative ranking of characteristics associated with local foods and a high WTP. Respondents ranked organically grown much lower than support local farmers, and 79% were WTP an average 17% price premium for local foods. Ross et al.[64] and Jekanowski et al.[65] found similar results in their surveys in Maine and Indiana, respectively. Zumwalt[60] surveyed consumers in four Midwest states about their attitudes for local, organic and all-natural foods. Forty-three percent of respondents were willing to pay at least 10% more for local foods, and while taste, quality and nutrition ranked highest, 70% rated support local farmer as very or extremely important; organic rated as the least important attribute (only 25% rated it as very or extremely important). Conversely, only 2.2% indicated supporting farmers/local farmers as one of their top two reasons for buying organic. Loureiro and Hine[66] found that WTP is higher for local food than organic food in Colorado; on average, consumers are willing to pay 9.37% more for local and 6.64% more for organic. Brown[67] and Schneider and Francis[68] found similar results for Missouri and Nebraska, respectively.

More recent studies find even higher WTP for local food (e.g., Darby et al.[69], Toler et al.[70], Adams and Adams[11]). For example, Toler et al.[70] report that consumers in Oklahoma are willing to pay 33% more for a generic local good and 70% more if the farmer is perceived as less well off compared to the consumer. Also, Adams and Adams[11] report WTP for a generic local good ranging from 48 to 107% more, on average, among three distinct groups of farmers' market shoppers in Florida. In addition to finding higher average WTP for local food, studies are finding a higher share of respondents associating local food with very positive environmental and social outcomes. For example, Zepeda and Leviten-Reid[71] found that supporting local farms was important to about half of so-called alternative consumers in Wisconsin, and they viewed local as providing direct environmental, economic, community and health benefits. Hartman Group[72] found similar views.

Discussion

Schneider and Francis[68] review the literature on local foods from 1984 to 2003 and argue that preference for local foods is 'rather inconclusive, indicating both weak and strong consumer preferences for local foods' (p. 253). Rather than viewing consumer perceptions and WTP for local food as static during this time period, we contend that there was a sea change in both perceptions and WTP that is coincident with the shift from deep organic to 'organic lite'. See Table 2 for a summary of select local food studies in the US.

We document a significant shift in consumers' perceptions of and WTP for local and organic food. In particular, changes in consumer views are coincident with the passage of the Organic Food Production Act of 1990 and the subsequent Organic Rule issued by the USDA. We note a distinct turn in the way consumers view both organic and local food, beginning with Wolf[61] and Gallons et al.[59]. Over the past decade, perceptions of local food have become much more positive, and consumers have indicated an increasingly high WTP for local food as compared to organic.

The shift in preferences and WTP from organic to local has been largely a result of consumers turning away from industrialization of organic agriculture, as previously discussed. The concept of 'local' is possibly more defensible than organic was, particularly given the genesis of the local movement in opposition to 'organic lite'. The movement resulted from dissatisfaction with the health and environmental effects of a modern and industrial agricultural system that co-opted the organic food market[73], and activists see it as a way to 'reclaim the heart and soul of organics' that became less about a social and political statement and more about a method of production[74]. If most consumers view 'local' as broadly defined to include sustainability, community food security, support for small farmers and a host of other issues, it may be seen as mutually exclusive from industrial agriculture.

The shift in preferences to local foods is also concomitant with a shift in individual consumption of fresh fruits and vegetables[75], which has been steadily increasing throughout the late 1980s and 1990s. Consumers are increasingly choosing where they shop based on the quality of produce, often leading them to key local food outlets such as farmers' markets and CSAs[10]. The push toward local food has also been driven in part by the restaurant industry and chefs, having discovered that high-quality, fresh and good priced produced can be obtained within the local food market[73]. For example, Cafe 150, the food cafe that caters to employees at Google headquarters, sources all its food within a 150 mile radius[76]. The Chefs Collaborative website is a network of chefs that works with professionals in the culinary industry to foster a more sustainable food supply by improving the means to source food locally.

The shift in the way consumers view organic and local food has significant consequences for the food system. Local has supplanted organic as the fastest growing

Table 2. Summary of select local food studies in the US.

Study	Date of study	*N*	Location and method	Local foods preference	Notes
Kezis et al.[54]	Not stated	2375	Maine, Delaware, W. Virginia: random sample mail survey	Weak	Produce origin much less important than quality, appearance, convenience and variety
Lockeretz[55]	1984	656	Massachusetts: intercept interview at supermarkets, farmers' markets and agricultural fairs	Weak	Only 14% at farmers' market or agricultural fair mentioned 'support local farms' as reason for shopping there, and just over half prefer local; at supermarkets, drops to 27% preferring local
Eastwood et al.[56]	1985	231	Tennessee: random sample interviews	Very weak	50% WTP premium for local tomatoes, negative WTP premium for other local goods; 'care where grown' has insignificant impact on WTP. Freshness/quality as main concern
Bruhn et al.[57]	1989	400	California: open-ended supermarket interviews	Weak	Only 13% expected to pay a premium for locally grown; 78% said origin not important. For tomatoes, 26% would pay 15–20 cents more/lb
Govindasamy et al.[53]	1990	656	New Jersey: random sample mail survey	Very weak	Locally grown, country of origin among least important of 19 characteristics; health value and absence of pesticides ranked 4th and 5th
Thomson and Kelvin[77]	1993	1214	Pennsylvania: intercept interviews at supermarkets and farmers' markets	Weak	9.9% strong, 25.4% moderate and 40.3% weak preference for local. 58.8% of these, primarily to know how food was grown
Jekanowski et al.[65]	1994	324	Indiana: random telephone survey	Moderate	58.8% highly likely to purchase local food products from a grocery store, 39.3% neutral or somewhat likely
Wolf[61]	1995	404	California: random sample interviews	Moderate	Locally grown rated as somewhat to very desirable (3.8 on a 5-point scale), above grown organically (3.2), but 8 other attributes rated above grown locally. Freshness/quality rated above 4.5
Gallons et al.[59]	1995	1205	Delaware: random sample mail survey, direct market consumers	Moderate	Only 5% often buy from direct market; produce selection, locally grown, and like to help farmers were first, second and third most important of 13 reasons for buying at direct markets. Organically grown rated much lower
Kezis et al.[63]	1995	239	Maine: farmers' market interviews	Moderate	72% WTP average 17% price premium. Support local farmers as second most important of nine reasons after quality. Health and food safety ranked 4th
Ross et al.[64]	1997	376	Maine: workplace 'interventions' and surveys	Moderate	76–84% prefer locally grown, but attitudes and preferences regarding local food not significant in regression model
Loureiro and Hine[66]	2000	437	Colorado: intercept surveys in supermarkets	Moderate	43.4% WTP >5% more for organic; 52.7% WTP >5% more for local. Mean WTP premium 6.64% for organic, 9.37% for local
Brown[67]	2000	544	Missouri: random sample mail survey	Moderate	21% WTP a price premium >5%, but quality and freshness deemed most important
Zumwalt[60]	2001	500	Nebraska, Iowa, Missouri, Wisconsin: random sample telephone interviews. Regarding attitudes on local, organic and all-natural	Strong	42.8% WTP at least 10% more; of 12 attributes, taste, quality, nutrition and price most important, but 70% rated 'support local family' as very or extremely important. Organic rated least important (25% rated it very or extremely important)

Table 2 (Continued)

Study	Date of study	*N*	Location and method	Local foods preference	Notes
Zepeda and Leviten-Reid[71]	2002–2003	48	Wisconsin: focus groups	Moderate	Supporting local farms is important to ~50% of 'alternative' consumers, who see it as providing economic, community and health benefits
Schneider and Francis[68]	2003	207	Nebraska: random sample telephone survey	Strong	36% are WTP a price premium >10%, and all-natural and organic food rated as least important of local food characteristics
Wolf et al.[62]	2003–2004	336	California: farmers' market intercept surveys	Moderate	Grown locally rated as moderately desirable, and far above grown organically. Organically grown rated as slightly desirable and rated lowest. Freshness, quality and price rated highest. Good for environment, locally grown rated next highest. Organically grown rated lowest
Darby et al.[69]	2005–2006	530	Ohio: intercept surveys at farmers' markets, farm stores and grocery stores	Strong	WTP premium for local strawberries $0.48 at grocery stores and $0.92 at direct market; also WTP $0.17 at grocery stores and $0.42 at farmers'/direct markets for small farm attribute
Adams and Adams[11]	2007	79	Florida: intercept surveys at farmers' markets	Strong	Three distinct groups of shoppers WTP 48–107% more than nonlocal
Toler et al.[70]	2008	100	Oklahoma: intercept surveys at farmers' markets, grocery stores	Strong	WTP 32.8% more for local, 70% more if local farmer perceived as less well off

segment of the retail food market and has the capacity to change the structure of the food system in ways that organic agriculture did not. While 'organic lite' is associated with a change in production, processing and labeling practices, it did not lead to major changes in the long chain structure of the food system. If positive views of local food continue to strengthen, we may see even faster growth in the local food market, and in direct markets such as CSAs, producer–consumer cooperatives and farmers' markets. These changes may lead to improved community food security and fewer food deserts, more financial stability for small farmers, improvements in consumer health that are linked to eating more fresh and unprocessed foods, and other important environmental and societal impacts. It is too soon to tell whether these trends will be durable, but a successful local food system will require not just high demand, but accessibility. It is crucial that policy-makers pay meaningful attention to developing and supporting the local food system. For example, city and county planning offices have the capacity to greatly assist in building the infrastructure necessary for a thriving local food system[78]. Rather than setting locales for farmers' markets in an *ad hoc* fashion, city redevelopment campaigns can allocate sites specific to the sale of local foods and design policies that encourage the growth of CSAs and farm cooperatives[78].

Even if the trends in consumer preferences for local food continue, there may be changes to the nature of local food as there was with organics. Savvy companies are already using the local concept in their marketing. For example, Frito-Lay recently began a marketing campaign dubbed 'Lay's Local' that emphasized their use of potatoes grown near their factories[79,80]. In 2008, Wal-Mart announced a commitment to source more local produce in an effort to keep food prices low, stating it expected to source about $4 million in locally grown fruits and vegetables from various farms across the US[81]. Critics warn that the retail giant is likely to source its 'local' food from a very small number of large farms, effectively shutting out smaller operations[81]. The minimum requirements for a local grower to supply Wal-Mart include: (1) be equipped with UPC bar code technology; (2) have $2 million in commercial liability insurance; and (3) have a financial stability rating. These requirements are likely out of the reach of small local farms[82].

Although there is a clear turn in the preferences for local food, there still exists a great deal of confusion about local and organic food characteristics. Bodini and Naspetti[83] document that in some cases local and organic food are direct substitutes for one another and in other cases they are complementary. For example, they found that consumers tend to think of organic food as safer, but of less quality than local food. In particular, consumers who infrequently buy organic products are more likely to confuse local food products with organic food products, thinking them to be one and the same. Hughner et al.[84] synthesized the empirical research on organic food demand and found that

many consumers buy organic food because they believe it supports the local economy, a factor also emphasized by proponents of local food. This may suggest the opportunity to market some foods as being both local and organic.

The potential confusion between organic and local food stems in part from the relatively abstract concept of the meaning of 'local'. Recent studies indicate that there is no widely accepted definition of 'local' by consumers[11,73]. Local can mean anything from food miles to a social movement. Whole Foods, a natural foods retail operation, defines a product as local if the total transport time from farm to store is seven or fewer hours by truck[85]. Local is defined by Wal-Mart to be a particular state border[82]. Some argue for a system of geographical indications that would protect the local economy, assure consumers and allow them to properly identify credible products, and lower transaction costs[73]. One of the benefits of such a system would be relieving consumers of the burden of getting to know farmers[10]. A concrete definition of 'local' could alleviate consumer confusion, but it has important marketing implications. A geographic definition of local foods (such as a county) or a temporal definition (such as from farm to fork in a day) increases the potential for product differentiation and marketing[69], but may lead to 'local lite' if companies attempt to meet minimal standards.

Conclusion

We trace the change in consumer perceptions and WTP for local and organic food over the past few decades. When viewing them as dynamic rather than static (e.g., Schneider and Francis[68]) our exploration uncovers a turn in the demand for local food that is significant to the broader context of the food system. Various drivers may have contributed to the shift toward local food, such as greater concern about industrialized organic agriculture and greater consumption of fresh produce. We indicate that the change is coincident with the development of federal organic standards and the arrival of 'organic lite'. Our analysis contributes to the growing body of literature on factors driving local food purchases.

The increase in interest and WTP for local food is a boon to small farms, and could lead to structural changes in the food system that have major impacts on environmental and social externalities associated with industrial agriculture. However, it is too soon to tell whether these changes in consumer preferences will translate to a fundamental change in the broader food system. Several factors could seriously impact the success of local food: trends in consumer preferences may subside; large agribusinesses may find a way to co-opt local food into 'local lite' as was the case with organic food; access to local food may continue to be an issue; and consumer confusion about what constitutes 'local' may dampen interest.

Our analysis highlights several interesting interrelationships between local and organic food demand, but we acknowledge that varied and complex factors are driving the apparent change toward local foods, and several critical assumptions are inherent in the research examined in this paper. There are several fertile areas for future research on local food.

While much of the previous work has focused on local and organic food as satisfying essentially similar needs, questions arise as to the nature of consumers' views of organic and local. To what extent do food miles embody the broader notions of community, sustainability, etc.? How does experience with organic and/or local food impact demand for the other? Additional research is needed to identify and understand people who are concerned with ecological footprint (i.e., food miles) of moving food versus those who are primarily concerned with community economic development, ethics, anti-corporate sentiment and other strong motivators for local food purchases. Also, the thrust toward local food is often assumed as structural change in food demand, but many consumers may view local food as a novelty, and demand for it may not be sustained in the long run.

We are also lacking a thorough understanding of an integrated local food system that begins with the small- to medium-sized farms and ends with the retail outlet. What is the appropriate role, if any, for the processor or wholesaler in a local food system? How can collaboration between retail grocers and small farms be best structured to facilitate the local food economy? As noted in Guptill and Wilkins[10], there are several institutional barriers to local producers supplying large retailers. What policies can local authorities use to improve access to local food? Little attention has been paid to the planning and building of the local food system infrastructure and facilitating the growth and expansion of the local food market[77]. Also, while there is a variety of outlets for local food, there is a lack of knowledge as to what represents the most rewarding outlet for local food producers. For example, are farmers' markets better placed in an urban center for greater access to consumers or are they better placed at the rural–urban fringe for better access to producers? Finally, much debate in the popular literature has focused on whether or not a local food industry could support the demand for the current population. Research on how an alternative agricultural system based on local food can complement, or to some extent replace, the existing industrialized system is needed.

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Book Review

Food, Farming and Faith. By Gary W. Fick. State University of New York Press, Albany, NY. 2008. 223 p. $14.98, Euro 12.1, ISBN 978-0-7914-7384-9 (paperback: alkaline paper).

Food, Farming and Faith focuses on the teachings of the Bible that describe ancient agricultural and cultural practices, with the aim to describe our agricultural history and to provide guidance for the development of more sustainable agricultural systems. In addition, the author attempts to show how the Bible's teaching can be used as a basis for overcoming other global challenges such as our expanding population, degradation of natural resources, lack of women's rights and poverty. In this modern age, we can forget the historical roots of our agricultural practices, even those of us involved with agriculture. Dr Fick's reminder serves to reconnect us, as well as encourage us to look to the past for solutions for the future.

Throughout the book, Dr Fick includes biblical passages, his interpretation of their meaning and the value the passage can have toward the development of more sustainable agricultural systems. Readers would quickly agree with most of the author's interpretations of biblical passages, given the self-explanatory nature of the passages. Dr Fick includes many passages that provide good farming advice such as planting a diversity of crops, weeding and plowing and irrigating as needed. However, the author's interpretations of a few passages are less understandable or convincing. In one case, the author gives a passage and interprets its meaning as suggesting a need for reduced tillage, although the passage itself makes no mention of needing to reduce tillage. In other cases, the actual passage is not given or cited, leaving the reader unclear on the basis of the interpretation. Such weakly supported interpretations may be off-putting to some readers. But these readers may be less likely to simply dismiss the author's arguments, due to the author's straightforward, jargon-free writing style and the inclusion of many personal farming experiences, which make the book feel more like a fireside chat than a scientific thesis. This warm, personal approach seems to both acknowledge its scientific shortcomings and point out the value of one's personal experience. This approach also may help to put the non-religious and skeptical reader more at ease and willing to listen to the well thought out perspective of the author who is clearly a very intelligent, caring and experienced agriculturalist and human being. If we can listen to and consider differing opinions, we will progress, as farmers, as humans and as a society. One cannot help but think that the relaxed atmosphere Dr Fick creates with his writing style is an intentional effort to foster this type of consideration from his readers and if so, he succeeds.

The addition of other global challenges, such as population, degradation of natural resources, lack of women's rights and poverty, helps to broaden the book's appeal and relevancy. Again, Dr Fick includes biblical passages that he feels can guide us to creating solutions to particular problems. However, as was the case with interpreting agriculturally related passages, the passages included often seem too general in their advice. In some cases, the reader could arrive at different and even opposite interpretations than those of the author, and the author seems to be well aware of this. Dr Fick presents his interpretations clearly and without dogma, which tends to provoke thought rather than blind acceptance or rejection by the reader, despite at times not having strong evidence to support his interpretations. Still, the reader may not feel convinced that the Bible's teachings are clear enough to be truly relevant or beneficial to our progress in overcoming these global challenges. In fact, it would be easy to argue that some of the Bible's teachings, on women's rights for example, are contradictory at best and counterproductive at worst. The author gives the impression of wanting the Bible to be used to a greater extent as a guidance in addressing these global concerns. However, the biblical passages given seem to be somewhat vague in their guidance and weak on detailed solutions, which is understandable given the unprecedented scale of the global challenges we face. The author gives many examples of the Bible's wisdom, and so his underlying assertion that the Bible can provide guidance cannot be quickly dismissed. However, many readers would have likely enjoyed the author's thoughts on how to apply biblical generalities to create practical solutions for our time. Still, the degree to which many of our global challenges are, to some extent, addressed in the Bible is likely to be surprising to many readers.

Dr Fick succeeds in writing a thought-provoking book that is a worthwhile read for everyone interested in sustainable agriculture and its relationship to the Bible. He reminds us of our connection to the past. His clear, warmly personal style that is free of scientific jargon, invites even the skeptic to consider his valuable perspectives as we seek solutions toward a more sustainable future.

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